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Methodology for deterministic geological modelling of the Forsmark site

Application to the development of the final repository for spent nuclear fuel

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Keywords: Object-based modelling, Geoscientific single-hole interpretation, Geological single-tunnel interpretation, Deformation zone, Rock domain, Sheet joint, Potentially critical structure.

Preface

A series of methodology reports support the programmes for investigation and modelling during the execution of planned underground constructions at Forsmark. The series includes the following disciplines: geometric modelling of ground elevation and regolith, deterministic geological modelling, discrete fracture network (DFN) modelling (stochastic, semi-stochastic and deterministic modelling of structural-hydraulic fracture data), rock mechanics modelling, thermal properties modelling, integrated hydrological and hydrogeological modelling, hydrogeochemical modelling, and transport modelling. Report numbers (ID), acronyms, and titles are shown below.

The methodology presented in this report covers techniques to identify and deterministically model rock domains and structures that might influence the layout or extent of the repository for spent nuclear fuel, or the canister positioning and integrity of such a repository.

Although the contents of this report focus on the Forsmark site and SKB's needs for deterministic geological modelling during the underground constructions of the spent fuel repository, the methodology is also applicable to the whole area around Forsmark, including the planned extension of the existing repository for low- to intermediate radioactive waste in Forsmark.

This report has been developed by Jan Hermanson (WSP) and Jesper Petersson (GEOS) with continuous and strong support from Peter Hultgren and Lillemor Claesson-Liljedahl. Especially appreciated have been constructive and comprehensive review comments from Jussi Mattila and Ismo Aaltonen. Other key individuals and experts that have contributed to the project are gratefully acknowledged, which includes, among others, Assen Simeonov, Sven Follin, Anders Winberg, Raymond Munier, Ingemar Markström and Christofer Zakrevski.

ID	Acronym	Title
R-20-11	DFNMM1	Methodology for discrete fracture network modelling of the Forsmark site. Part 1 – Concepts, Data and Interpretation Methods
R-20-12	DFNMM2	Methodology for discrete fracture network modelling of the Forsmark site. Part 2 – Application examples
R-20-13	RMMM	Methodology for rock mechanics modelling of the Forsmark site
R-20-14	HGMM	Methodology for hydrological and hydrogeological modelling of the Forsmark site
R-20-15	HCMM	Methodology for hydrochemical modelling of the Forsmark site
R-20-16	ERMM	Methodology for elevation and regolith modelling of the Forsmark site
R-20-17	TRPMM	Methodology for site descriptive and safety assessment transport modelling of the Forsmark site
R-20-18	THPMM1	Methodology for modelling of thermal properties of the Forsmark site. Part 1 – Recommended data and interpretation methods
R-20-19	THPMM2	Methodology for modelling of thermal properties of the Forsmark site. Part 2 – Background and methodology development

Summary

The presented methodology utilizes the foundations laid out in Munier et al. (2003) and Munier and Hermanson (2001), which were used and improved with the development and testing of conceptual geological models during a period of five years of site descriptive modelling at both Forsmark and Laxemar (Stephens et al. 2007, Wahlgren et al. 2008). The present methodology is focused on handling the type of information that will be available during the construction of the repository, namely borehole and tunnel data. This allows a continued use of the previously tested methodology for geological modelling based predominantly on surface-based information.

Object-based modelling is introduced with the intent of being flexible, capable of handling large amounts of data and allowing multiple individuals of the modelling teams working simultaneously on separately defined model volumes. To accomplish this, the building blocks for processing and interpreting information from boreholes and tunnels are described. The main components of object-based modelling are geoscientific single-hole interpretation and geological single-tunnel interpretation, the latter being a new method that will form an additional structured building block to the subsequent 3D modelling process.

These preceding steps of multidisciplinary interpretations provide the basis for describing the 3D modelling process of structures and rock domains:

- Using underground observations not necessarily connected to surface observations,
- to a finer level of detail identify deformation zones and rock units,
- to objectively address uncertainty, both through utilizing conditioned stochastic simulation of the spatial extent of deterministic objects, as well as quantifying uncertainties in interpretation and the object properties, and
- to provide continuous development and improvement of the conceptual site understanding for post-closure safety and as support for rock mechanical, hydrogeological and hydrogeochemical modelling.

Sammanfattning

Metodiken som presenteras i denna rapport omfattar identifiering och deterministisk modellering av bergdomäner och strukturer med eventuell betydelse för utformningen för kapselsäkerhet i djupförvaret för utbränt kärnbränsle. De grundläggande principerna är de samma som tidigare introducerats av Munier et al. (2003) och Munier and Hermanson (2001) som tillämpats vid utveckling av konceptuella geologiska modeller under en period på mer än fem år av plastbeskrivande modellering i Forsmark och Laxemar (Stephens et al. 2007, Wahlgren et al. 2008). Denna uppdaterade metodik fokuserar på modellering baserat på borrhåls- och tunneldata som i stor mängd förväntas bli tillgängliga vid byggnation av djupförvaret.

För ökad flexibilitet, hantering av stora datamängder och för att möjliggöra parallellt arbete i olika modellvolymer har objektbaserad modellering introducerats. Som underlag för denna modellering beskrivs även parameterisering och tolkning av information från borrhål och tunnlar. De huvudsakliga komponenterna är geovetenskaplig enhålstolkning och geologisk entunneltolkning, där den senare är en ny metod för att generera byggstenar till den efterföljande 3D modelleringen.

Målsättningen med processen för 3D modellering av strukturer och bergdomäner kan beskrivas enligt följande:

- Användande av observationer under mark som inte nödvändigtvis är kopplade till observationer på ytan,
- med en högre detaljeringsgrad identifiera deformationszoner och bergenheter,
- objektiv osäkerhetshantering, både genom konditionerad stokastisk simulering av utsträckningen på deterministiska objekt samt konfidensgrad för tolkade deterministiska objekt och dess geologiska egenskaper, och
- kontinuerligt öka den konceptuella platsförståelsen för säkerhetsanalys samt som stöd för bergmekanisk, hydrogeologisk och hydrogeokemisk modellering.

Contents

1 Introduction

1.1 Background

The radioactive waste disposal system of the Swedish Nuclear Fuel and Waste Management Company (SKB) involves emplacement of spent nuclear fuel in a geological repository at ca 500 m depth in crystalline bedrock. The KBS-3V disposal concept involves encapsulation of spent fuel rods in canisters made up of cast iron inserts covered by an outer copper shell. The canisters are to be embedded in a bentonite buffer in vertical deposition holes (∅ 1.75 m, ca 8 m long). Deposition tunnels are back-filled with bentonite blocks and are strategically sealed with plugs at their respective entrances.

SKB plans to construct the geological repository at Forsmark, some 150 km NNE of Stockholm. Surface-based site investigations and associated site descriptive modelling were performed 2002 through 2008, followed by an evaluation of long-term safety and a compilation of a license application to construct the repository, submitted to the authorities in March 2011. The repository will be a nuclear facility, which entails basic requirements regarding both the cavern stability of the facility during the operational stage and of radiological safety (including seismic stability) during the operational stage and after closure of the facility. The demands related to post-closure long-term safety of the repository are addressed by specified technical design requirements formulated by SKB together with its Finnish sister organization Posiva (cf Posiva SKB 2017).

Detailed site investigations will be carried out in the immediate vicinity of the repository during its construction with three principal aims: 1) to provide means for detailed adaptation of the planned facility layout to bedrock conditions, 2) provision of information required to assess fulfilment of design requirements concerning post-closure safety, and 3) to continuously improve the site understanding through repetitive prediction-outcome studies. This includes guidance of engineering-related decisions and needs associated with the design and construction work during the establishment of the final repository. The collected investigation data and associated models of the bedrock and surface systems ultimately constitute the basis for assessments of post-closure safety.

Prior to and during construction it is necessary that techniques, methods and methodologies are developed and improved with a learning-as-you-go approach. A cornerstone in these efforts is the further development of the geoscientific modelling methodology. The approach is an overarching methodology for those geoscientific disciplines which are considered being most important for repository design and safety assessment, with separate methodology reports covering the disciplines of bedrock geology, rock mechanics, Quaternary geology, hydrogeology, hydrochemistry, bedrock solute transport- and thermal conductivity, also including *Discrete Fracture Network* (DFN) modelling methodology.

This report presents the methodology for maintaining and presenting deterministic geological models, based on data generated during the construction and operation of the repository for spent nuclear fuel. The basic principles of the methodology are the same as for the site descriptive modelling performed and completed in conjunction with the preceding surface-based site investigations, with an overall workflow starting with collection of raw data, an intermediate interpretative stage and finally the construction of three-dimensional geological models. The concepts of the presented methodology are intended to be general, but with intended explicit use in Forsmark, including interaction with the *Site Characterization Database* (SICADA) , the *Spatial Data Engine* (SDE) database and the *Rock Visualization System* (RVS), specifically designed for this purpose by SKB.

The basis for the presented methodology is the strategy report for development of geological models based on site investigations from the ground surface by Munier et al. (2003), which in turn incorporates the methodology for geometrical modelling of deformation zones and the fractured rock outside these zones, as described by Munier and Hermanson (2001). The latter methodology has been tested and improved during the site descriptive modelling at both Forsmark and Laxemar, with the development and testing of geological conceptual models during five years of site investigations (Stephens et al. 2007, Wahlgren et al. 2008). The intent has been to further develop those parts of the methodology that are applicable to detailed site investigations in and in the vicinity of the repository, predominantly based on borehole and tunnel information. This allows a continued use of the previously comprehensively tested and improved methodology for geological modelling based predominantly on surface-based information. In order to provide a basis for long-term safety assessments and engineering-related decisions, geological models with a higher degree of detail of the repository volume are key elements to evaluate the need of support/sealing measures and the technical design requirements concerning the barrier function of the rock. The significance of data obtained at the ground surface, the backbone in the preceding site-scale geological modelling, will decrease markedly during the underground site investigations. Consequently, the methodology outlined in the current report focuses on modelling based on geological data from boreholes and underground openings that successively become available as the construction of repository accesses and subsequent tunnelling associated with deposition areas proceeds.

1.2 Objectives and scope

This report describes methods to deterministically model rock domains and structures that might influence the layout or extent of the repository or be critical for canister positioning and integrity. The latter, denoted critical structures of Class 3 (see Posiva SKB 2017), includes local minor deformation zones, but to some extent also individual fractures. The deterministic modelling thus intends to capture all potentially critical structures (Class 2 to 3) that intersects a repository part (including canister positions).

The fracture network in the rock volume surrounding the repository is handled stochastically by discrete fracture network (DFN) analysis, integrating geological and hydrogeological fracture data and is covered in Selroos et al. (2022). To assess the uncertainty of the potential variability in size of deformation zones that do not have geologically specified spatial constraints, DFN methodology is used to stochastically assess effects of variable size beyond the deterministic geometry. In this context the mutual dependencies between methodologies for geological and hydrogeological modelling are emphasized for the establishment of deterministic and stochastic models of connected conductive structures.

The objective has been to develop a methodology that is flexible, capable of handling large amounts of data and allowing multiple individuals of the modelling teams to working simultaneously on separately defined model volumes. To meet the foreseen complexity, a process of *object-based modelling* is being introduced. In this approach each modelled geometric object is stored in a spatial database with accompanying geometric relations and constraints, with full traceability of object versions. The method allows for multiple users working simultaneously on information from different parts of the repository.

The methodology also includes objectives and scope for the interpretative phases before initiating 3D modelling. The main interpretative components being an updated geoscientific single-hole interpretation (GSHI) and a new geological single-tunnel interpretation (STI). The STI will form an additional structured building block to the subsequent 3D modelling process. The basis for this analysis is the new tunnel mapping data that will be acquired during the excavations of the access ramp, central area and tunnels of the deposition areas, respectively.

The methodology is applicable to the entire repository, including the regolith stripped rock exposures in proximity of repository accesses and in surface operation areas and builds on acquiring data from routine investigations performed within the context of the construction process. However, it is primarily in the deposition areas that highly resolved geological models are needed for decisions regarding the deposition process, and consequently, where the most extensive investigation campaigns will be performed. Attaining this last level of detail is in many ways a learning process with opportunities to successively optimize the methodology.

In summary, a great deal of testing of the methodology presented herein remains after the development has been performed of the various components that underpin the object-based modelling process. SKB is currently developing RVS with the aim to manage object-based modelling but the methodology is flexible enough for other tools to also be used in the future. Input is also expected from users applying the methodology in various modelling projects prior to the onset of repository construction, but also during the actual construction in Forsmark. It is also recommended to review progress and, if applicable, make use of good practice of the geological modelling made at the Finnish repository for spent nuclear fuel at ONKALO®[1] which is currently developed by Posiva.

The scope has also included a reassessment of the handling of uncertainty and confidence in the interpretation process. Previous discussions of the topic have been presented by Andersson et al. (2002), Andersson (2003) and Munier et al. (2003). The new methodology presents methods to quantify and evaluate the confidence of both geometric and interpretative aspects.

1.3 General work procedure

The geological modelling is based on geoscientific interpretation, which in turn is based on processing and analysis of the raw data acquired during the construction and operation of the repository. The process is similar to that introduced by Munier et al. (2003) for the site descriptive modelling carried out during the surface-based site investigations, including three levels of interpretation as presented in Section 1.5; method-specific, integrative and multidisciplinary interpretation. However, based on experiences from previous SKB modelling projects, there now exists an explicit goal that the process of multidisciplinary interpretation will start *before* the onset of the actual geometrical modelling[2]. The single-hole interpretation can be viewed as an example of the development to introduce early multidisciplinary work. During the previous site descriptive modelling, it was a purely integrative interpretation method, which mainly provided a synthesis of geological and geophysical borehole data. In this report, the interpretation process has been extended to include hydrogeological borehole information and the method has consequently been renamed to geoscientific single-hole interpretation, underscoring that it now incorporates a wider, multidisciplinary interpretation. Even if no hydrogeochemical and rock mechanical data are considered in the interpretation process, it is emphasized that specialists of these disciplines participate in the interpretation process to provide both a thorough understanding of the borehole and a joint communication tool between the different disciplines.

The general work procedure is summarised in Figure 1-1 describing the execution and mutual dependencies of geological/geoscientific investigations, intervening interpretations and deterministic modelling before and after excavation of a tunnel section. The use of a *Tunnel Boring Machine* (TBM) in the access ramp will remove the ability to use information from pilot boreholes and the access to the excavation front. This will limit the work process to only include detailed geological mapping along the tunnel. The use of multiple excavation fronts in the deposition area will enable a slightly different order of execution for the interpretative activities of deposition tunnels, as illustrated in Figure 1-2.

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[1] ONKALO® is a registered trademark of Posiva Oy

[2] Stenberg L, Simeonov A, 2016. Strategy for modelling and description of rocks and deformation zones at Äspö HRL. SKBdoc 1555236 ver 1.0, Svensk Kärnbränslehantering AB. (Internal document.)

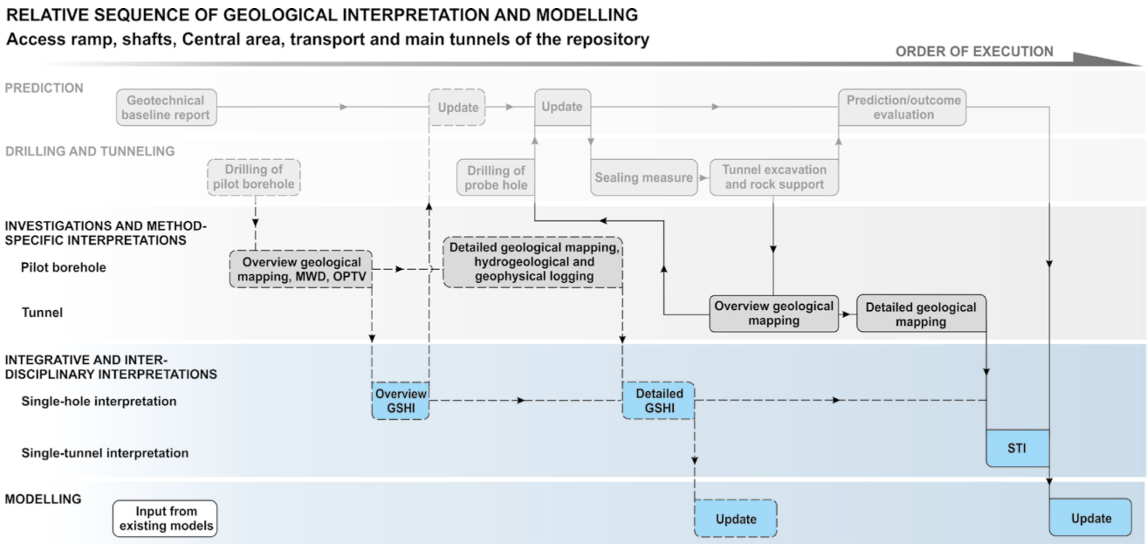

Figure 1-1. The order of execution and relative dependencies of the geological investigations and interpretative activities, which follows excavation of a typical tunnel section along the repository infrastructure. Modelling is included to illustrate when action is recommended. The flow chart does not describe decisions needed to proceed with each step. This will be presented in SKB's detailed investigation programs.

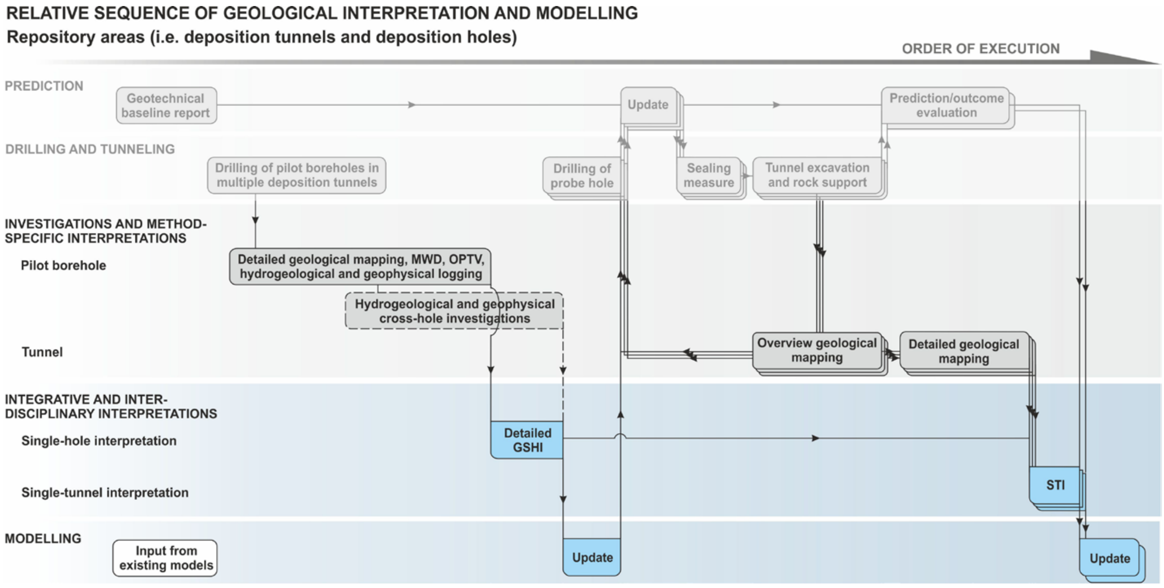

Figure 1-2. The order of execution and relative dependencies of the geological investigations and interpretative activities, following excavation of one or more deposition tunnels. Modelling is included to illustrate when action is recommended. The flow chart does not describe decisions needed to proceed with each step. This will be detailed in SKB operational programs.

The process of constructing geological models can be separated into two sequences as illustrated in Figure 1-3; one that covers the continuous modelling performed as part of the ongoing excavations and one that is executed at defined milestones. At defined milestones a fixed collection of data and interpretations are used for modelling. Each milestone modelling reflects a certain level of understanding and can be compared with the defined modelling stages of SDM-site (i.e. the Forsmark version 1.2, 1.3 etc). The sequence of modelling milestones for the detailed site descriptions of Forsmark will be described in detail in the operational programmes for the repository accesses and the deposition areas.

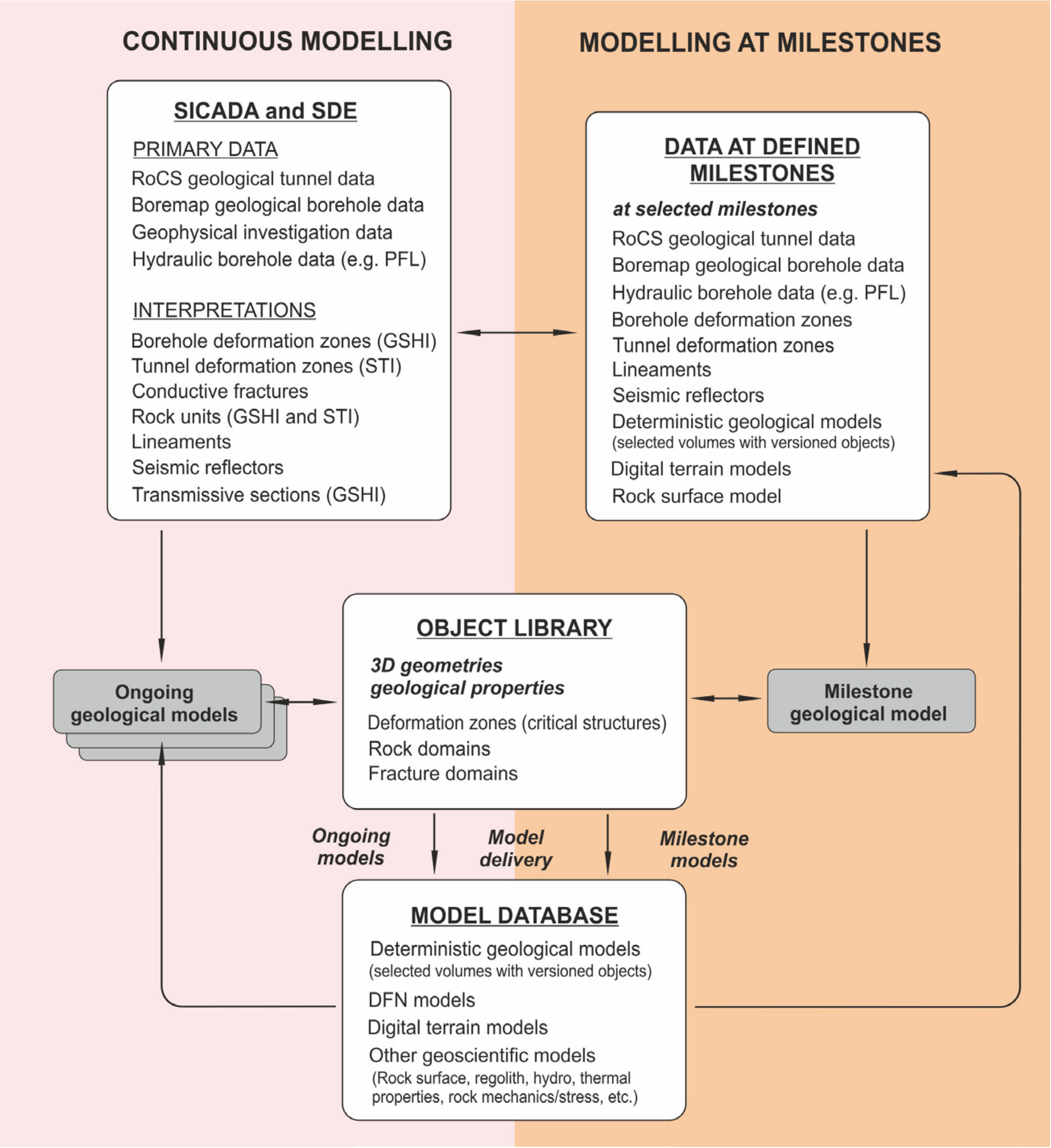

***Figure 1-3.** Flowchart describing the relations between primary data, modelled 3D objects and output models. The purpose of the object library and the model database is further explained under Section 5.2.*

1.4 Content and structure of this report

This report has inherited much of its structure from the methodology report for geological site descriptive modelling presented by Munier et al. (2003). The reader is initially introduced to some general terminology commonly used throughout this report (Section 1.5). This is followed by a chapter on the repository layout, along with the prerequisites for the development of geometric geological models in conjunction with the construction and operation of a final repository for spent nuclear fuel in Forsmark (Chapter 2). In addition to a brief review of the methodology and assumptions upon which conceptual understanding of the site geology and existing geological models are based, this chapter presents an overview of the planned facility layout and applicable technical design requirements with bearing on the geological modelling. Chapter 3 concerns the primary data, which constitute the basis for the geological modelling. Moreover, the chapter outlines the investigation strategies in different parts of the repository, together with main sub-surface investigation methods and, to some extent, the degree of method-specific interpretation. A further description of the main methods used for data acquisition for deterministic geological modelling is presented in Appendix 1. Chapter 4 concerns the combined assessment of the primary data sets by integrative and multidisciplinary interpretation to provide usable building blocks for the three-dimensional modelling work. Chapter 5 presents the central theme of the report, the methodology for the object-based geological modelling. Chapter 6 discusses the handling of uncertainty and confidence at different points of the modelling process. Appendices 2 and 3 present details of the methodologies of geoscientific single-hole interpretation and geological single-tunnel interpretation, respectively. Appendix 4 provides details concerning different object types and their geological properties. Appendix 5 contains details regarding the review process of geological modelling.

1.5 Terminology

Being a multidisciplinary methodology, this section has been included to ensure a consistent use of terminology and facilitate integration. A list of relevant terms is presented in Table 1-1 with their abbreviations, Swedish translations and cross-references to other sections for explanation. Only terms that relate to geological features of central importance for the completion of the methodology have been included with definitions and further explanation in this section. The details are generally based on text from previously published SKB reports, principally Munier et al. (2003).

Table 1-1. Geological terms in alphabetical order with their abbreviations, Swedish translations and cross-references to other sections for explanation.

Term	Abbreviation	Swedish translation	Chapter/Section
Borehole deformation zone	BDZ	Borrhålsdeformationszon identifierad vid detaljerad GSHI	4.1 and Appendix 2
Borehole fracture zone	BFZ	Spröd zon identifierad vid översiktlig GSHI	4.1 and Appendix 2
Critical structure	CS	Kritisk struktur	1.5 and 2.3
Critical volume	CV	Kritisk volym	1.5 and 2.3
Confidence level	CL	Konfidensnivå	6
Deformation zone	DZ	Deformationszon	1.5
Deterministically modelled structures	DMS	Deterministiskt modellerade strukturer	2.1.1
Discrete fracture network	DFN	Diskret spricknätverk	6.4
Geoscientific single-hole interpretation	GSHI	Geovetenskaplig enhålstolkning	1.3, 4.1 and Appendix 2
Domain	-	Domän	1.5
Full perimeter intersection	FPI	Spricka som genomskär hela tunnelns periferi	1.5
Geological Model	-	Geologisk modell	1.5 and 5.2
Geological Object	-	Geologiskt objekt	1.5 and 5.2
Geological Object Library	-	Geologiskt objektsbibliotek	1.5 and 5.2
Geological single-hole interpretation	SHI	Geologisk enhålstolkning	1.3, 4.1 and Appendix 2
Geologic single-tunnel interpretation	STI	Geologisk entunneltolkning	4.2 and Appendix 3
Geological tunnel mapping	-	Geologisk tunnelkartering	3.1.2 and Appendix 1

Term	Abbreviation	Swedish translation	Chapter/Section
Geotechnical baseline report	GBR	Ingenjörsgeologisk prognos	-
Integrative interpretation	-	Samtolkning	1.5 and 4
Large fracture	-	Stor spricka	1.5
Multidisciplinary interpretation	-	Ämnesövergripande tolkning	1.5 and 4
Method-specific interpretation	-	Metod-specifik tolkning	1.5 and 4
Overview geoscientific single-hole interpretation	Overview GSHI	Förenklad geovetenskaplig enhålstolkning	1.3, 4.1 and Appendix 2
Overview geological tunnel mapping	-	Översiktlig geologisk tunnelkartering	3.1.2 and Appendix 1
Possible deformation zone	PDZ	Möjlig deformationszon	4.1 and Appendix 2
Potentially critical structure	PCS	Potentiellt kritisk struktur	2.3 and 5.6
Potentially critical volume	PCV	Potentiellt kritisk volym	2.3 and 5.6
Remote mapping	-	Fjärrkartering	Fel! Hittar inte referenskälla. and Appendix 1
Sheet joint		Bankningsplan	5.4.8
Tunnel deformation zone	TDZ	Tunneldeformationszon	4.2 and Appendix 3
Unit		Enhet	1.5

Critical structure/volume

Posiva SKB (2017) define the terms critical structure (CS) and critical volume (CV) as structures and rock volumes with properties such that they can negatively impact the post-closure safety of a KBS-3 repository. The term embraces continuous single fractures and minor deformation zones that constitute potential risks for either secondary movements as a result of seismic events or inflow of groundwater of such magnitude that the design requirements are not fulfilled (Munier and Mattila 2015). See Section 2.3 for further details.

Deformation zone

The term deformation zone refers to a near planar structure with a small thickness relative to its lateral extent along which there is a concentration of brittle, ductile or combined brittle and ductile deformation.

Brittle deformation zones generally consist of one or several zones of crushed and/or intensely fractured material (fault core) flanked by fractured and/or hydrothermally altered rock (damage zone), see Figure 1-4. The latter need not show up symmetrically on both sides of the fault core. Fracture zones with a thickness of less than 10 cm were denoted “fractures” during the surface-based site descriptive modelling (Andersson et al. 2000a, b). A further reduction of the limiting thickness is stipulated by the more resolved scales employed in the detailed site investigations but set to approximately 1–2 cm for practical reasons of macroscopic tunnel mapping.

Based on the nomenclature originally set by Andersson et al. (2000a) and Andersson (2003), SKB has subdivided deformation zones into regional, local major and local minor deformation zones and fractures according to Table 1-2. . However, the degree of determinism is expected to increase in models of various parts of the repository, largely dependent on geometry and distances between underground openings (i.e. data density). Local minor deformation zones and, to some extent, individual large fractures, can hence be described deterministically.

Intervals with deformation zone like properties that are identified along boreholes and tunnels during the single-hole and single-tunnel interpretations are referred to as borehole and tunnel deformation zones, respectively. The approach has been adopted to separate inferred intercepts of deformation zones along individual boreholes and tunnels from deformation zones modelled as combinations of such interpretations. Additionally, the approach provides information whether identification was based on borehole observations or more reliable tunnel data, and thereby reflecting the degree of uncertainty in identification.

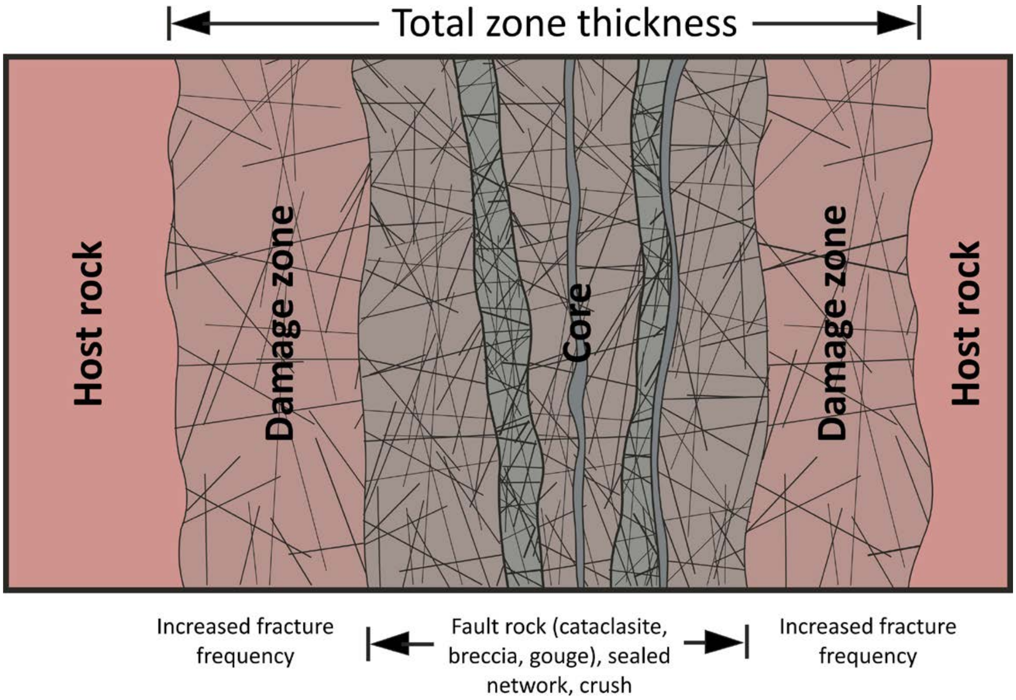

Figure 1-4. Schematic illustration of a brittle deformation zone, modified after Munier et al. (2003).

Table 1-2. Subdivision of deformation zones used by SKB during the site descriptive modelling stage. Modified from Andersson et al. (2000a). Figures for length and thickness are approximate.

Designation	Length	Thickness	Ambition for description
Regional deformation zones	> 10 km	> 100 m	Deterministic
Local major deformation zones	1–10 km	5–100 m	Deterministic
Local minor deformation zones	100–1 000 m	0.01–5 m	Deterministic, stochastic and/or semi-stochastic
Fractures	< 100 m	< 0.1 m	Stochastic and conditioned stochastic (adjacent to underground openings deterministic)

Deformation zones identified during the development of SDM-Site were denoted ZFM followed by an indication of the orientation of the zone and two to eight letters or digits, for example ZFMWNW0123 (i.e. WNW orientation). The naming system for deformation zones used previously was tied primarily to lineaments for the steeply dipping deformation zones, and seismic reflector IDs for the gently dipping zones, with some exceptions. Each steep zone also had an indicative horizontal direction in their name which led to very long names, which in addition could change over time as new data are acquired.

The naming of new deformation zones identified from sub-surface investigations shall follow a convention of using a prefix of ZFM and a continuous numbering starting from 4001. An example of a new zone name is ZFM4032.The reason for starting at 4001 is to separate the naming convention used in SDM-Site (which have zone names up to 3400). If needed a suffix can also be added to the name.

Domain

The concept of using domains is to combine several units with similar characteristics with respect to a particular property (see **Unit**, below) to simplify the description of the modelled rock mass. For rock domains the combination of rock units are based on properties such as:

- Mineralogical composition, and to some extent on grain-size and texture of the dominant rock type.
- Degree of bedrock homogeneity in combination with the style and degree of ductile deformation.
- The occurrence of alteration (in the Forsmark area, albitization).

Fracture domains in Forsmark refers to the character and intensity of fracturing in the rock volume outside deformation zones (statistical homogeneity; cf Olofsson et al. 2007).

Subdivision of the rock mass into domains is based on the principle of "space filling", where the model volume is filled by geometric objects in such a way that no part remains uninformed. Domains of a specific type connect seamlessly and cannot overlap. However, rock domains can be overlain by other volumetric and surface objects such as fracture domain volumes, deformation zones and fracture surfaces.

New rock and fracture domains identified from sub-surface investigations shall have a prefix of RFM or FFM, respectively, and shall have a continuous numbering following the previously used numbering in SDM-Site. An example of a new rock domain is RFM46. If needed a suffix can also be added to the name.

Full Perimeter Intersection (FPI) Fracture

The term was introduced to represent and account for fractures of unknown size but being of such extent that their intersection with a tunnel can be traced around the full perimeter of the tunnel face (Figure 1-5). The FPIs can be used as a conservative proxy to identify and avoid potential deposition hole positions intersected by fractures potentially large enough to constitute a (seismic) hazard (i.e. critical structures) and adjust the deposition hole position accordingly (Munier 2006). However, with a typical fracture size distribution, an overwhelming majority of the FPIs are clearly under the critical size.

***Figure 1-5**. An example of a fracture with a full perimeter intersection, the TASS tunnel, Äspö HRL. View of the tunnel roof, based on a photogrammetric compilation.*

Geological Object

A Geological Object is the interpreted three-dimensional geometry accompanied by metadata describing the geological nature of the object as illustrated in Figure 1-6. Essentially, there are four main types of objects that will populate the geological model: Rock domains, fracture domains, deterministically modelled fractures and deformation zones. Metadata are the compiled knowledge and interpreted geological object properties in text format or conveyed as illustrations, graphs etc.

Geological Object Library

All individual 3D *geological objects* that are interpreted and modelled are stored in a separate spatial object library. As illustrated in Figure 1-6, each object is stored with its specified geometric position and extent, its version and details of its creator and metadata describing the geological nature of the object. For full traceability, the objects can be checked out, edited and re-entered like a document handling system.

Geological Model

A *geological model* is the desired selection of interpreted and modelled geological objects extracted from the object library within a specified volume of interest. The geological model can be an assemblage of objects in the volume of one or several parts of the repository and can be exported to a model database, primarily for downstream usage. See also the definition of the site descriptive model below.

Interpretation

Method-specific interpretation

This term will be used for the processing and interpretation of raw data. It is generally carried out by the contractor during or immediately after data acquisition, and it is generally based on the application of a geological or geophysical technique. This type of interpretation takes place according to standard and generally accepted procedures (method descriptions) and is carried out before the data are stored in SICADA and SDE databases. An example is geophysical borehole logs which are constructed semi-automatically from the data recorded during a geophysical logging. The results of this type of interpretation is regarded as a primary data set for the purposes of the modelling described in this report, but it is important to be aware that the interpretation, albeit standardised and uncontroversial, has been an integral part of its acquisition.

Figure 1-6. *Illustration of the concept of a geological object that consists of the geometry and its corresponding metadata. The object is stored in a spatial object library from where it can be checked out, edited and re-entered with full traceability.*

Integrative interpretation

This term will be used for the data processing and interpretation carried out by SKB's experts in preparation for geological modelling. Integrative interpretation generally involves combining primary data sets from different methods to establish a synthesis of available data within a particular discipline (e.g. combining geological data from the borehole or tunnel mapping during an initial step of the geoscientific single-hole or single-tunnel interpretation). It makes use of the primary data sets stored in SICADA and SDE, and the results form an important part of the input into the multidisciplinary interpretation and eventually 3D modelling. The results of integrative interpretation can be revised later based on the acquisition of new data, perhaps using a new method. The products of the integrative interpretations are for example borehole and tunnel deformation zones, which consist of two components: geometry (i.e. orientation, thickness, diameter, etc) and metadata (including a property compilation).

Multidisciplinary interpretation

This term is used for the type of interpretation requiring interaction amongst different geoscientific disciplines. It is the principal step of the single-hole and single-tunnel interpretation. The multidisciplinary interpretation is a necessary bridge between data interpretation and the deterministic modelling. Although multidisciplinary interpretation should be regarded as an integral part in the step between the data assembly and modelling, it is important it is carried through the entire modelling process.

Sheet Joints

Sheet joints are dilatational, brittle structures, characteristically developed parallel or nearly parallel to topographic surfaces and divide the shallow rock mass into thin layers or sheets. The joints are thought to develop parallel to the two greatest principal compressive stresses in the rock mass with inferred connection to unloading of the bedrock. Most sheet joints have hairline apertures, but a significant proportion of the inferred sheet joints displays conspicuous apertures exceeding 0.1 m and many of them are filled with sediment (cf Carlsson 1979).

To emphasize the hydraulic importance of the sheet joints in the uppermost 150 m of bedrock, the term shallow bedrock aquifer (SBA) was introduced by Follin (2008). Even if the sheet joints of the SBA have no immediate effect on the long-term canister safety, it is considered critical for the hydraulic connectivity of the system as it impact the hydraulic gradient and hence affect groundwater flow at depth.

Sheet joints have the prefix JFM beginning with 001. The reason for this terminology is that sheet joints are different in their formation mode to deformation zones, as further described in Section 5.4.8.

Site Descriptive Model

A *site descriptive model* (SDM) is an integrated model for geology, thermal conductivity, rock mechanics, hydrogeology, hydrogeochemistry, bedrock solute transport and a description of the surface system. The analysis and modelling of geological data from the site provide a foundation for the modelling work carried out in other disciplines (hydrogeology, thermal conductivity, rock mechanics and hydrogeochemistry) and for the design of the repository.

Unit

A rock unit is the smallest, non-divided lithological volume in a geometric model (cf Figure 1-7). For lithologies with anomalously low thermal conductivity (such as amphibolite in Forsmark), this is in the order of 1–2 m along a borehole or tunnel (see Section 5.5 for further details). It is defined based on the composition, grain size and inferred relative age of the dominant rock type. Other geological features include the degree of lithological homogeneity, the degree and style of ductile deformation, and the occurrence of early-stage alteration (for example albitization in Forsmark) that affects the composition of the rock. Increased fracture frequency also helps to define and distinguish some rock units as a basis for fracture domain modelling.

It should be emphasized that this does not exclude a considerable small-scale variability within a single rock unit, for example due to the contribution of xenoliths and veins. Several rock units of similar character may occur along a single tunnel or borehole if the units are separated by one or more rock units of contrasting character; thus, unit boundaries cannot overlap in any model.

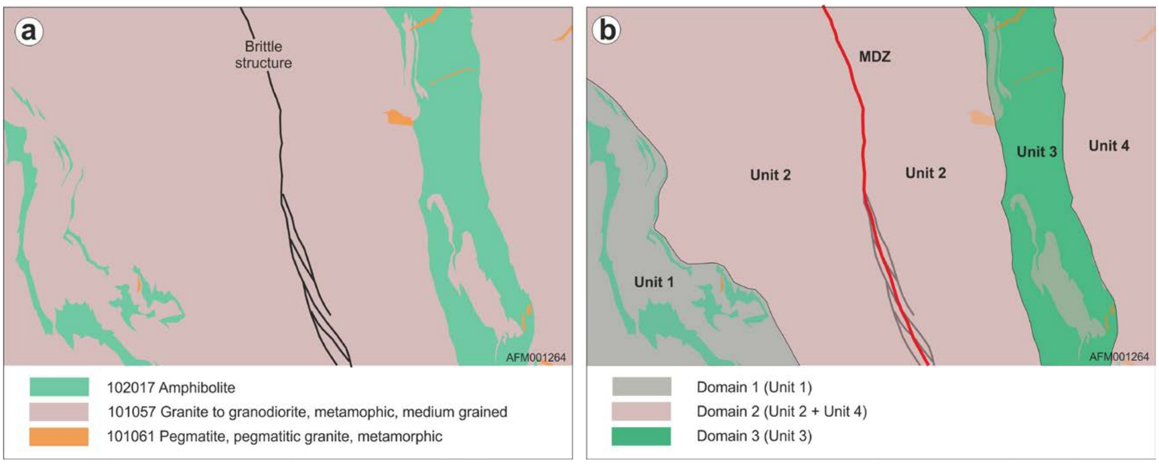

Figure 1-7*. Illustration of the concepts of units: (a) a hypothetical geological map showing the rock type distribution with an area characterised by swarms of amphibolitic veins in granodiorite, and (b) the same map subdivided into rock units. The field of view is approximately 20 × 30 m. Reworked from Munier et al. (2003).*

2 Prerequisites for geological modelling

2.1 Deterministic geological models for Forsmark

2.1.1 Overview of existing models

The geological basis for the site descriptive model (SDM-Site) at Forsmark (SKB 2008) relies on the geometric models of rock domains, deformation zones and fracture domains, which were developed in several stages up to the Forsmark stage 2.2 modelling (Olofsson et al. 2007, Stephens et al. 2007). Deterministic models for rock domains and deformation zones were subsequently developed as the basis for the extension of the final repository for short-lived radioactive waste (SFR), project SDM-PSU (*Projekt SFR-Utbyggnad*; SKB 2013). The Forsmark version 2.2 deterministic model for rock domains and deformation zones has subsequently been updated to model version 2.3 (Stephens and Simeonov 2015), which takes the deformation zone model for SFR into account (Curtis et al. 2011).

3D geological models were produced for two different volumes during the site descriptive modelling for Forsmark, termed regional and local, respectively. The rock domain models of the regional and local model volumes differ only in the division of RFM029 into two domains in the local model volume, namely RFM029 and RFM045.

Considerations of with respect to distance (Munier and Hökmark 2004) have guided the selection of a bounding size for deformation zones included in the local and regional volume models. Thus, deformation zones that have produced trace lengths at the ground surface of 3 000 m or more are included in the deterministic regional volume model. For the local deformation zone model, it was deemed practical to set the size limit at structures with trace lengths at the ground surface at 1 000 m. Where the available high-resolution, surface magnetic data permitted, some minor zones that are shorter than 1 000 m have been modelled deterministically and assigned properties, but these were not included in the local block model of deformation zones (Figure 2-1). Since sizes of gently dipping zones are difficult to estimate, and since these zones are significant from a hydrogeological point of view, it was decided to include all the identified gently dipping zones in both the local and regional models.

The deformation zone modelling for the SFR extension project SDM-PSU has also been performed in corresponding regional and local volumes devised for PSU (Curtis et al. 2011). The resolution of the SFR regional model corresponds to the local model of the Forsmark SDM, containing all modelled deformation zones with a surface trace length of ≥ 1 000 m, whereas the local SDM-PSU model contains all deformation zones with trace lengths ≥ 300 m.

An investigation campaign initiated during 2010 for characterization of the uppermost 150 m of the bedrock, in proximity of the planned accesses and operation area of the final repository, has been the basis for minor local modifications of the deterministic deformation zone model version 2.3 of the Forsmark site. The outcome of this work was (1) locally more resolved boundaries than in the version 2.2 fracture domain model and (2) addition of one deformation zone along with slight geometrical adjustments of some of the deformation zones previously established for version 2.3 (see Follin 2019).

At the request of downstream users, a master version of the deformation zone model has been provided, by integrating the Forsmark version 2.3 (regional and local) with the SFR version 1.0 (regional and local) and the modifications to some deformation zones in the proximity of the planned accesses and operation area of the final repository[3]. This master version is named DMS (*Deterministically Modelled Structures*) and includes all deterministically modelled deformation zones and sheet joints, regardless of size. To attain consistency of the basic geometrical modelling principles in the DMS, several deformation zones have been adjusted with regards to their termination depth[4] and, in the case of the SFR version 1.0, also zone thickness (see below).

The fracture domain model is currently revised with regards to distribution of horizontal to sub-horizontal sheet joints in the near-surface realm of the so-called shallow bedrock aquifer (SBA) in Forsmark by using a conceptual semi-stochastic approach. Specifics on sheets joint deterministic modelling is presented in Section 5.4.8.

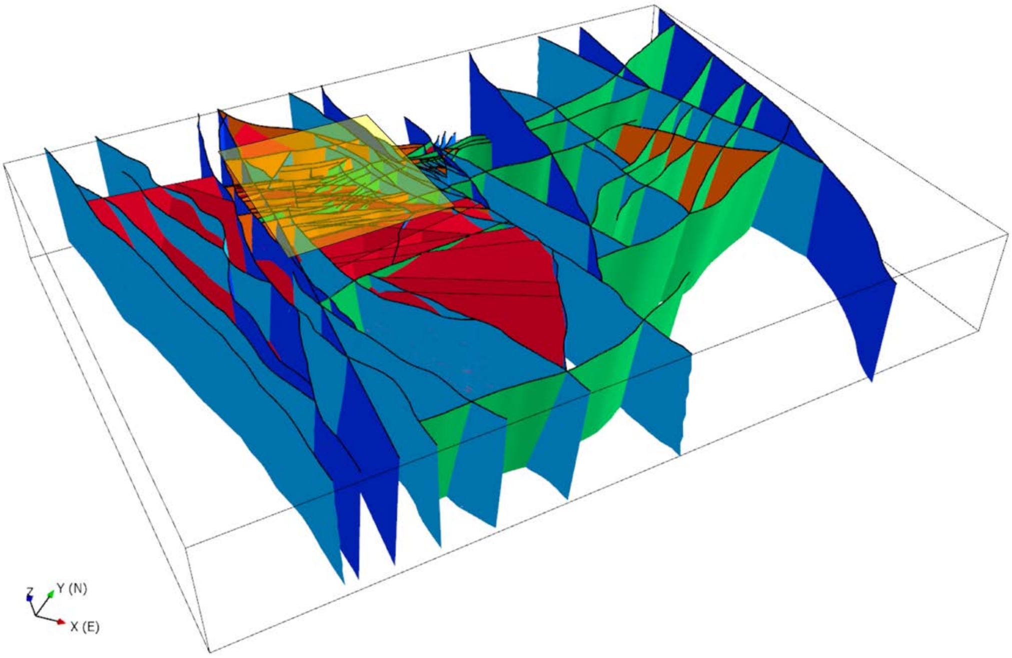

***Figure 2-1**. Three-dimensional visualization of the DMS 2020 inside the regional volume of SDM-Site, with a size of 15 × 11 × 2.1 km and the 15 km boundaries striking N45°E. The ground surface extent of the SDM-Site local model volume is marked in yellow.*

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[3] ZFMENE1061A – Geometrical adjustment based on data from HFM19, HFM40 and KFM24.
ZFMENE2248 – Geometrical adjustment based on data from HFM41, KFM26 and KFM27.
ZFMENE2120 – Geometrical adjustment based on data from KFM23.
ZFMNNW1205 – renamed to ZFMNNW1205A. Geometrical adjustment based on data from KFM13 and KFM23.
ZFMNNW1205B – added to the model based on data from KFM08B, KFM13, KFM21 and AFM001393.
Truncation of ZFMNE3134 towards ZFMWNW0835.
Removal of ZFMNNE3130.

Dahlin P, Petersson J, Mattsson H, 2017. Geological single-hole interpretation of KFM24. SKB P-16-29, Svensk Kärnbränslehantering AB.

Follin S (ed), 2019. Multidisciplinary description of the access area of a planned spent nuclear fuel repository in Forsmark prior to construction. SKB R-17-13, Svensk Kärnbränslehantering AB.

[4] Changed termination depth for a large number of deformation zones:

- The general principle is that a steeply dipping deformation zone should be modelled to a depth equal to the length of the zone's surface trace (z = 0).
- Deformation zones that exceed 2 100 m in trace length at the ground surface terminate at the base of the Forsmark regional model volume (i.e. –2 100 m a.s.l.), with no consideration of the cut-off classes introduced for SFR version 1.0 (Curtis et al. 2011).
- Termination depth was rounded off to the closest 50 m a.s.l. for zones with trace lengths ≥ 1 000 m, and to the closest 10 m a.s.l. for zones with trace lengths < 1 000 m.
- The termination of splays (with the prefix "B" and "C") is controlled by the termination depth of the main deformation zone (with the prefix "A").

2.1.2 Modelling approaches in SDM-Site and SDM-PSU

The rock domain models for the Forsmark site were primarily established from surface mapping of the bedrock. The orientation of ductile structural data from both the surface and from boreholes, as well as critical borehole intersections for rock domain boundaries were used in the projection of rock domains at the surface down to the base of the model. The following assumptions were inherent in the rock domain modelling procedure:

- The mean values of the orientation of planar ductile structures (banding and tectonic foliation), as measured at the surface and in boreholes, are assumed to provide an estimate of the orientation of the contacts between the rock domains.
- Since the rock domains at the surface are major geological features and the contacts between the domains are predominantly steeply dipping, these domains are assumed to extend downwards to the base of the regional model volume.
- Lenses of ultramafic, mafic and intermediate rocks mapped at the surface are assumed to plunge downwards in approximately the orientation of the mineral stretching lineation as flattened rod-shaped entities, and to extend to, at least, the base of the regional model volume.
- Two domains at the surface (RFM017 and RFM022) are modelled as a gently dipping xenolith and laccolith, respectively, and do not extend to the base of the regional model volume.
- The orientation of the contacts between rock units in boreholes that correspond to rock domain boundaries were not employed in the modelling, only their locations.

For the geometrical modelling of deformation zones it was assumed that low magnetic lineaments form a sound basis for the identification of steeply dipping (> 70°) or vertical deformation zones (Stephens et al. 2007), along which magnetite in the bedrock, to a variable extent, has been hematized by reactions with fluids. The assumption finds strong support in extensive field control both by excavation and drilling across several lineaments defined by magnetic minima (e.g. Petersson et al. 2007, Stephens et al. 2008). Lineaments based on depressions in the unconformity between the Precambrian crystalline bedrock and the regolith (Quaternary deposits) have only been utilised in the areas where the magnetic data are of poorer quality, for example in the vicinity of the nuclear power plant (SKB 2005). On the basis of these assumptions, steeply dipping or vertical zones have been identified by an integration of the interpretation of these lineaments with borehole data. Data from a few outcrops and excavations have also been considered. The matching of a lineament to a possible deformation zone in a borehole makes use of the overall character of the zone in the borehole, in particular the analysis of the orientation of fractures along the zone, where sealed fractures, sealed fracture networks, open and partly open fractures, and crush zones were distinguished from each other. The general distribution pattern for the fracture orientation in each zone intercept was used as a guideline to link that borehole section to a suitably oriented lineament. Thus, the orientation of fractures along an inferred zone has only been used as a support for the correlation procedure.

The strike of a zone was assumed to be determined by the trend of the matching lineament. The decision to match a low-magnetic lineament with a particular borehole or tunnel intersection determines the dip of the zone. The dip of zones that are related solely to lineaments and lack borehole intersections was estimated by comparison with the dip of high confidence zones, which intersect one or more boreholes and show a similar strike. The along-strike truncation of steeply dipping or vertical zones was steered by the truncation pattern of the corresponding lineaments and follows the conceptual understanding of the site. In this manner, the length on the ground surface of such zones corresponds to the length of the matching lineament. Truncation of zones at depth, which lack interpreted intersections with other zones, was carried out with the assumption that the zone extends to a depth that is approximately the same as its trace length at the surface.

Gently dipping zones were assumed to be identified by an integration of seismic reflectors and borehole data (Stephens et al. 2015). As for the steeply dipping or vertical zones, the matching of a reflector to a possible deformation zone in a borehole follows the same analytical procedure with support from fracture orientation data. The geometry of the gently dipping zones was provided by the inferred orientation of the corresponding seismic reflector. In accordance with the conceptual understanding of the site, the gently dipping zones were assumed to truncate, both along their strike and in the down-dip direction, against the spatially nearest regional or major, steeply dipping deformation zone.

In the Forsmark SDM, deformation zone thickness is defined with a constant width along the entire zone and includes both damage zone and fault core. This differs from the inferred thickness observed in each individual borehole, tunnel, or surface intercept of a zone. The geometric thickness has either been defined as a mean value of the inferred thicknesses in all intersecting boreholes (Figure 2-2a) or by the inferred thickness in one or more borehole intercepts, judged to be representative. Thus, parts of an inferred zone intercept along a borehole can occur outside the modelled zone's geometric boundaries and vice versa (Figure 2-2a). For the SFR deformation zone model, the geometric thickness refers to the maximum inferred thickness (damage zone plus fault core) observed in the boreholes or tunnels that penetrate a zone (Figure 2-2b). In Olkiluoto, Posiva has used a third alternative by employing linear extrapolation of inferred zone thickness at each observation point (Figure 2-2c). The thickness of steeply dipping zones that lack data from borehole, tunnel or surface intersections has been estimated using a length-thickness correlation diagram (cf Stephens et al. 2007).

A high confidence of existence is applied to all zones that have been confirmed directly by geological data from a borehole or tunnel, or from outcrop observations at the ground surface. In general, indirect data (e.g. low magnetic lineament, seismic reflector) are also present. A medium confidence zone generally lacks direct confirmatory data and the zone has been identified solely by the occurrence of a low magnetic lineament or a seismic reflector. In a few cases, a zone has been classified as medium confidence based on low fracture frequency and limited bedrock alteration.

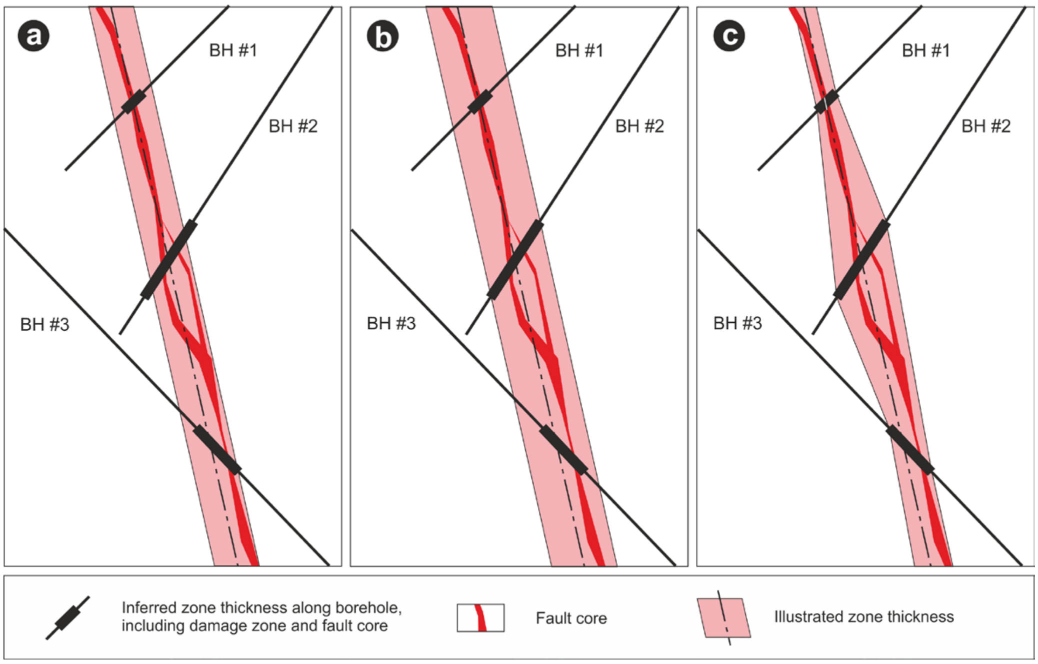


Figure 2-2. Methodology of illustrating modelled zone thickness relative to the inferred zone thickness from each location of observation. Zone thickness defined as (a) a mean value of the inferred thicknesses in all intersecting boreholes, and (b) the maximum inferred thickness observed in the intersecting boreholes (in this case BH #2) or (c) linear extrapolation of inferred zone thickness at each observation point.

The third component in the deterministic geological model for Forsmark is the fracture domain model (Olofsson et al. 2007), which primarily provided input to the DFN-modelling (see Figure 2-3). The geometric fracture domain model includes four fracture domains (FFM01, FFM02, FFM03 and FFM06) and is limited to the part of the Forsmark tectonic lens that lies inside the local model volume (i.e. RFM029 and RFM045). The division of the bedrock between deformation zones into fracture domains is based on the following considerations:

- A systematic assessment of the variation in the frequency of particularly horizontal to sub-horizontal, open and partly open fractures with depth along each borehole.
- The degree and character of the ductile strain and, to a large extent, the grain-size and compositional character of the rock domains.

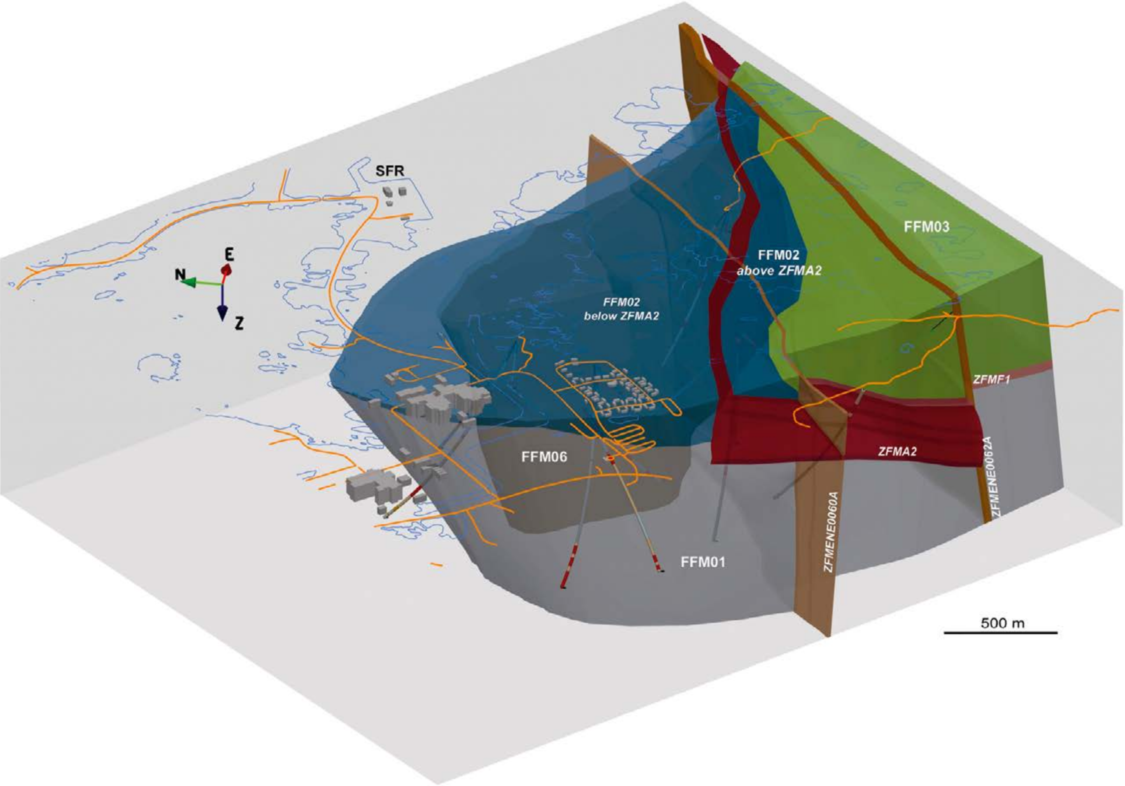


***Figure 2-3.** Three-dimensional view to the east–north–east showing the relationship between fracture domains and the deformation zones ZFMA2, ZFMF1, ZFMENE0060A and ZFMENE0062A. The local model block is shown in pale grey. From Olofsson et al. (2007).*

2.2 Repository facility and its layout

The final repository is designed with the overall objective of providing safety after closure for c 6000 canisters disposed at a depth of approximately 470 m. As a basis for SR-Site (SKB 2011) and the applications under the Nuclear Activities Act and the Environmental Code, the entire final repository has been designed to a level called Layout D2 (SKB 2009a). With a fulfilment of the Design Premises – Long Term Safety (SKB 2009b), the layout of a final repository within the tectonic lens in Forsmark requires an area of 4.4 km^2, and a total tunnel length of approximately 72 km. In Layout D2 (SKB 2009a), the final repository consists of four functional parts (Figure 2-4) with slightly differing performance requirements:

- Surface facilities.
- Access (ramp and shafts).
- Central area (providing logistics, services and infrastructure).
- Repository area with deposition areas (main tunnels, transport tunnels, deposition tunnels and deposition holes).

The surface facilities (the industrial area) comprise various civil structures and buildings above ground, which are connected to the underground central area by several shafts and a ramp. The location of the underground central area is dictated by the location of the surface facility and vice-versa. The access ramp is designed as a spiral down to repository depth with an approximate total length of nearly 5 km (i.e. average along-ramp inclination 1/10).

The central area will be in the north–western part of the repository area, which will be developed from this area towards the southeast (Figure 2-4). The repository area is divided into several deposition areas to enable investigation, construction, and deposition activities to proceed simultaneously in different parts of the repository. The layout of the deposition areas is largely constrained by the technical design requirements presented in Section 2.3, where the minimum distance between deposition tunnels and between deposition holes are determined with respect to existing structures impacting layout and the highest permissible buffer temperature. In the Forsmark tectonic lens the centre-to-centre spacing of the deposition holes is 6 or 6.8 m, depending on rock domain. The centre-to-centre spacing of the deposition tunnels is 40 m, regardless of rock domain, and the deposition tunnels will have a length of ≤ 300 m. The first deposition hole is located at least 20.6 m from the entrance to the deposition tunnel and the last deposition hole will be located 10 m from the end of the deposition tunnel. To minimize the tangential stress and minimise the risk of spalling (cf Martin 2005), the deposition tunnels will be aligned parallel to sub-parallel (±30°) to the maximum horizontal stress (the latter which has an azimuth of 145 ± 15° in Forsmark).

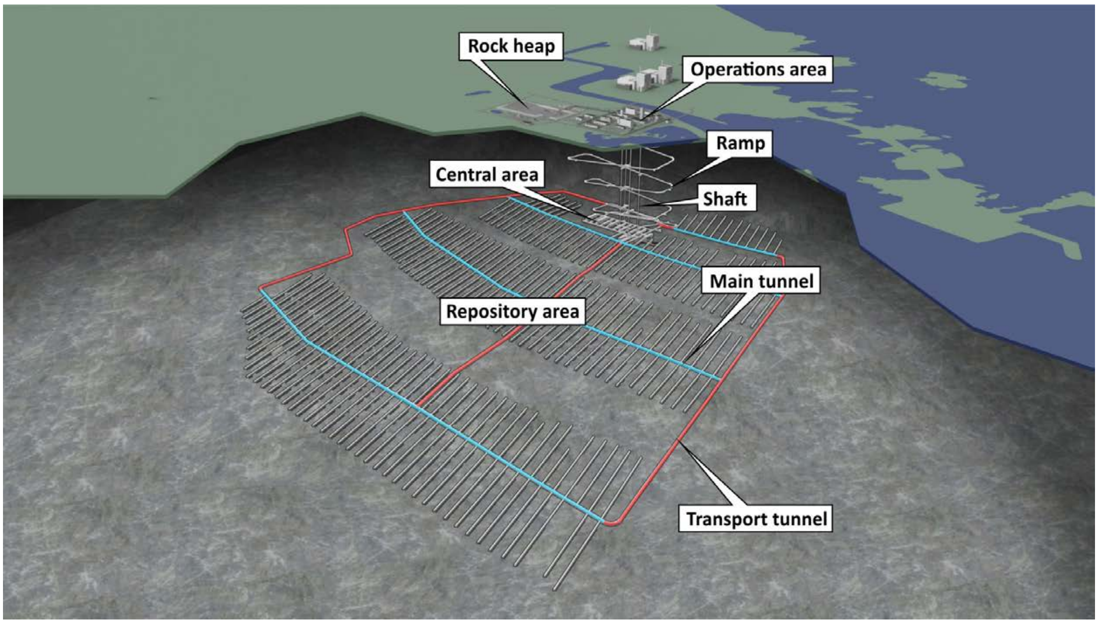


***Figure 2-4**. Conceptual illustration of the general layout of the final repository at Forsmark. Modified from SKB (2018).*

Given the constraints imposed on the deposition tunnels and deposition holes, a layout with four northeast–southwest aligned main tunnels, from which a number of deposition tunnels will emanate, has been proposed, whereas transport tunnels will be located along the boundaries and possibly outside of the tectonic lens to maximize the utilisation of the rock mass with eligible properties for deposition (see Figure 2-4).

More precise layout decisions with exact locations of some facility parts are site specific and highly dependent on the rock mass character, particularly the design and construction of the deposition areas. Thus, some issues can only be resolved during construction by concomitant investigations and modelling.

2.3 Technical design requirements applicable to Geology

One primary objective of the geological modelling is to provide a basis for developing a design of the repository that meets the requirements of post-closure safety. In SKB (2009b), a number of technical design requirements, which the underground openings shall conform to, have been formulated as a feedback from the SR-Can safety assessment (SKB 2006). A subsequent update of the technical design requirements, primarily based on the SR-Site safety assessment (SKB 2011), is presented in Posiva SKB (2017). The requirements cover both the adaptation of the design to the bedrock conditions and premises that must be fulfilled with respect to the function of the buffer and backfill.

A fulfilment of the inherent barrier function requirement of the rock, as listed by Posiva SKB (2017), is achieved by avoiding all structures of critical size and/or hydraulic conductivity, as well as rock types with low thermal conductivity. The identification of all such critical structures (Munier and Mattila 2015) is essential from a perspective of post closure safety and hence constitutes one of the primary purposes of the investigations and the subsequent interpretation and modelling.

For this purpose, Posiva SKB (2017) defines the terms *critical structure (CS)* and *critical volume (CV)* as structures or rock volumes with properties such that they can negatively impact the post-closure safety of a KBS-3 repository. The spatial extent of potentially critical structures cannot be revealed by visual observation in boreholes and tunnels, but requires 3D modelling and evaluation steps. Thus, the fulfilment of the requirement that a deposition area, deposition tunnel or canister position may not be intersected by a critical structure is not directly observable. If data over one volume are sparse it is important to be conservative in any assessment whether a structure should be classified as critical. Considering the uncertain nature of available geoscientific data in general, there will always be a component of expert judgement involved in such assessments. By considering the potential safety impact, critical structures and volumes are classified as follows with respect to their effects on the repository layout:

- **CS1/CV1** are structures/volumes with properties such that they cannot be accepted within the repository footprint. Consequently, they steer the location and boundary limits of the repository.
- **CS2/CV2** are structures/volumes with properties such that they cannot be accepted within deposition tunnels. Consequently, they influence the layout of the repository and steer the location and extent of deposition tunnels.
- **CS3/CV3** are structures/volumes with properties such that they cannot be accepted to intersect canister positions.

Following the classification introduced by Posiva SKB (2017) for critical structures and volumes, based on their effect on the repository layout, it is expected that all CS1/CV1 and virtually all CS2/CV2 have been identified during the site descriptive modelling completed in conjunction with the preceding site investigations. The occurrence of additional, currently unrecognized CS2/CV2 within the repository volume cannot be excluded, but the size of such geological features will undoubtedly be sufficient to allow confident identification at an early stage of the repository construction. Expected future changes in the geometry of identified and modelled structures can also affect the suitability classification. However, the challenge is the detection of CS3/CV3, with properties such that they could jeopardize the long-term safety of a canister if they intersect a deposition hole. Briefly, the CS3/CV3 embraces geological features, which display one or more of the following four critical properties, as further illustrated by schematic examples in Figure 2-5:

- Structures that constitute potential risks for secondary movements as a result of seismic events.
- Significant flow paths of groundwater.
- Rock volumes that significantly limit the thermal output from the deposited canisters.

A more specific definition of the term CS3 with regard to the displacement potential is proposed on the basis of the text in Cosgrove et al. (2006), with an adjustment of slip magnitude according to Fälth and Hökmark (2006): The term embraces any minor deformation zone along which slip of a critical magnitude (5 cm) might occur in response to a seismic event on a nearby fault. These will include the following:

- Discrete shear fractures (faults).
- Discrete extensional fractures (joints).
- Deformation zones of brittle, ductile or combined brittle and ductile character, regardless of whether there has or has not been a shear sense of movement along the zone.

Detailed geometry of these structures can be extremely varied ranging from single, relatively straight fractures to composite brittle to brittle-ductile features, including deformational concentrations to zone cores and numerous shorter fractures transmitting displacements between more extensive fault planes.

Geological assessment of the potential criticality will be made on the combined interpretation and modelled geometry of each structure/volume. Section 5.6 describes the process for identification and assessment of (A) potentially critical structures with a risk for shear and (C) potentially critical rock volumes with unfavourable thermal properties. The assessment of (B) significant groundwater flow paths cannot be assessed directly in the deterministic geological models and require further analysis through hydrogeological modelling.

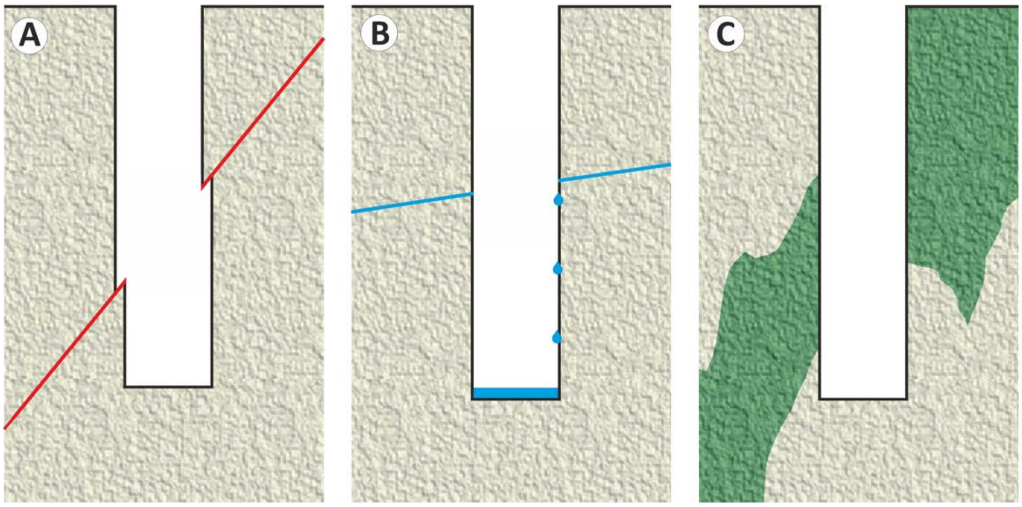


***Figure 2-5.** Schematic representations of deposition holes illustrating four different geological features regarded as critical structures or volumes of class 3: (A) Structure that constitutes a potential risk for secondary movements, (B) significant groundwater flow path, and (C) rock volume that significantly limits the thermal output from the deposited canisters.*

Size can be used as a proxy reflecting the inherent ability to host a sufficient slip exceeding the canister failure criterion (cf Cosgrove et al. 2006). As established by Munier (2006, 2010), the canister failure criterion consists of two parts. The first part, denoted the full perimeter criterion (FPC), refers to fractures or minor deformation zones that can be followed around the full perimeter of a deposition tunnel (so-called FPIs, see Section 1.5 for definition). If such FPI structures are extrapolated beyond the perimeter of the tunnel, any canister position intersected will be considered for rejection regardless of its true size (Figure 2-6C). The second part comprises potentially critical structures that do not intersect the deposition tunnel but are sufficiently close to intersect a relatively large number of canisters. Such structures are typically sub-horizontal or gently to moderately dipping with strikes parallel to the tunnel trend. An extended criterion, the EFPC, is defined as features intersecting five or more canister positions (Figure 2-6D). However, using the full perimeter criterion leads to an overly conservative result based on practical experiences (Mattila 2020, personal communication) from the development of Olkiluoto. Based on stochastic assessments of fracture data of Olkiluoto, the conclusion is that 70 % of all FPIs are formed by fractures that are less than the set critical diameter. Instead of using the full perimeter criterion, the methodology herein sets out a structured modelling process to deterministically quantify how structures are extrapolated beyond observations (see Section 5.4), which in turn leads to an improved assessment of the actual size of identified FPI's.

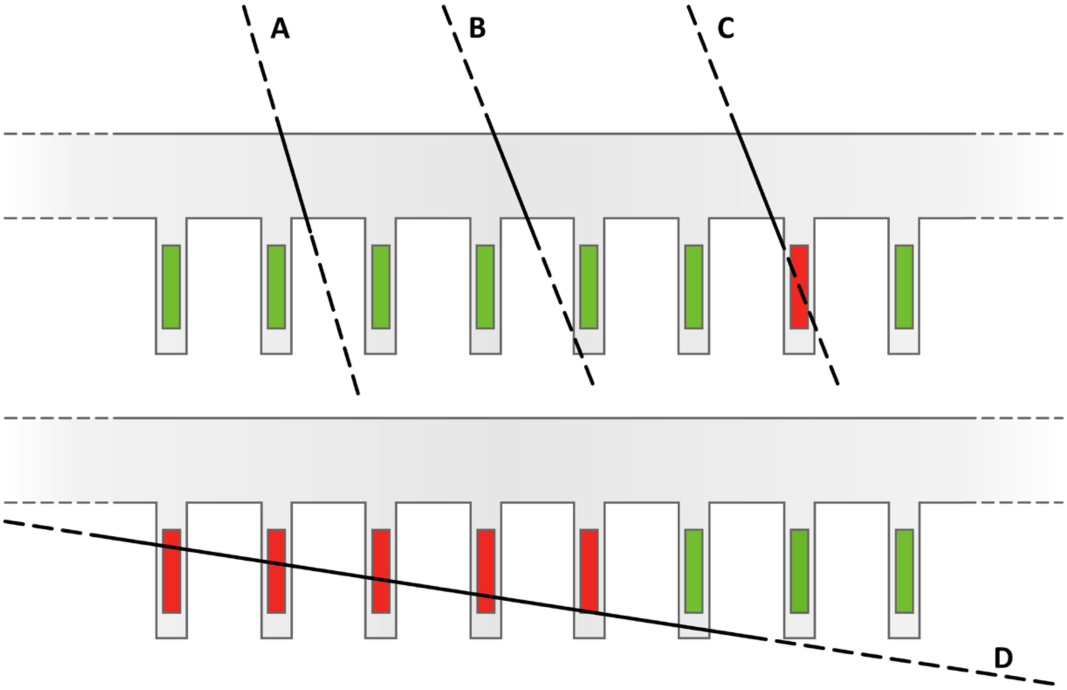


***Figure 2-6**. Illustration of the principle of the EFPC. A, B and C are FPI structures in the deposition tunnel, where C prevents deposition, unless it is possible to show that the size of the FPI structure is less than required for hosting 5 cm of slip. D is a structure that can be traced in more than five canister positions, with a resulting rejection. Modified from SKB (2010).*

3 Overview of planned geological and geophysical investigation methods

This chapter lists geological and geophysical investigation methods that are expected to be used during the tunnel constructions and an overview of the deployment of these investigations.

Descriptions of the geological and geophysical methods are available as “method descriptions” (Swedish: *metodbeskrivningar*), which, amongst other things, regulate in which form the primary data shall be delivered and to what extent method-specific interpretations are to be carried out. Method descriptions constitute an important component of the QA system employed by SKB. They are written in a manner to ensure that repetitive tasks are performed in a similar way during the detailed site investigations and that the delivered data are quality assured and traceable. The individual investigation methods intended for detailed site investigations are listed in Table 3-1. A condensed version of the method descriptions for geological borehole mapping and tunnel mapping are given in Appendix 1. For additional details, all MD documents are available from SKB upon request.

There are several geophysical and geological exploration methods that has been carried out from the air and ground surface during the preceding site investigations. Existing primary data obtained by these surface-based methods are essential components for modelling also during the tunnel construction, especially in the uppermost part of the rock mass. However, their significance decreases markedly as data from the repository tunnels and shafts successively become available. Due to their limited application underground, surface-based methods are not presented here; instead the reader is referred to the overview given by Munier et al. (2003).

Table 3-1. Summary of the main geological and geophysical methods expected to be used during the tunnel constructions as input to the 3D geological modelling.

#	Method	MD number	Comments on method-specific interpretation
Individual methods			
1	Radiometric age determination	MD 132.002	Absolute age determination of minerals and rocks, mainly to provide a basis of the description of the geological evolution of an area
2	Borehole mapping (Boremap)	MD 143.006	Systematic structural and petrographic description of rock cores, incl. sample analysis, preferably carried out together with item 3 and 6
3	Fracture mineral analysis	MD 144.001	Determination of fracture minerals, preferably carried out to support ocular identification during item 2 and 5
4	Tunnel and outcrop photogrammetry	MD 150.010	Photogrammetric background used in conjunction with item 5. Gives the 3D-geometry of outcrops, tunnels and other underground openings
5	Geological tunnel and outcrop mapping (RoCS)	MD 150.011	Systematic structural and petrographic description of outcrops, tunnels, and other underground openings. Preferably carried out together with item 4
6	Petrographic analysis	MD 160.001	Standard thin-section (polarising microscope) and powder (X-ray diffraction) methods
7	Geophysical borehole logging	MD 221.002 MD 221.003	A combination of techniques where the results are integrated into so-called pseudo-fracture and pseudo-lithology logs to support item 2 and the GSHI of Section 4.1
8	Borehole-wall imagery	MD 222.030	TV imagery of borehole wall (optical televiewer, and similar instrumentation), used in conjunction with rock cores (item 2)
9	Borehole deviation	MD 224.001	Deviation measurement of boreholes, used in conjunction with item 2
9	Petrophysics	MD 230.001	Measurement of physical properties of rocks (standard methods) in outcrop and on samples
10	Tunnel seismics	MD 242.001	Reflection seismic profiling for detection of discontinuities such as deformation zones and rock contacts
11	Ground penetration radar (GPR)	MD 251.003	Ground penetration radar with the main applicability to characterise EDZ
12	Tunnel resistivity	MD 212.005	Mis-á-la masse for detection of water-bearing deformation zones and associated alteration

3.1 Investigation methods for boreholes and tunnels

3.1.1 Borehole investigations

Geological logging of the pilot boreholes is conducted in the Boremap system (#2 in Table 3-1), which is a digital mapping system developed by SKB. The system integrates traditional core logging with information from an optical image of the borehole walls. Whereas the drill core provides most of the geological details, an oriented borehole image reveals geometric data in terms of orientation and location for the geological objects. In addition to this, the Boremap system offers the alternatives of mapping without borehole image, without drill core (percussion boreholes) and overview mapping.

A standard package of geophysical borehole investigations (#7 in Table 3-1) is carried out in each core drilled borehole which are then integrated into pseudo-fracture and pseudo-lithology logs to support the Boremap mapping and the subsequent GSHI (explained in Section 4.1).

Probe holes contribute less to the geological description by being limited to MWD and flow data, the amount of cement-based grout used in conjunction with passage of minor deformation zones, water consumption and pumped-out drainage water.

Hydrogeological investigations in cored and percussion boreholes are described in the detailed investigation programme (cf SKB 2018) and are not covered here.

3.1.2 Tunnel investigations

All geological mapping of exposed rock surfaces along underground openings and exposed surface outcrops will be carried out by using RoCS (#5 in Table 3-1). The mapping system is based on a digital mapping record created by photogrammetric means. The spatial location and extents of various geological objects are digitized on the photogrammetric 3D model, whereas the rock surfaces of the underground openings provide information on geological details that cannot be distinguished in the images.

The mapping is carried out in two levels of detail: overview mapping or detailed mapping.

In tunnels excavated by conventional methods, overview mapping is carried out directly after a new section has been excavated with the purpose to capture the most prominent geological features to support engineering related decisions. The detailed mapping is carried out well behind the excavation front or when the tunnel has been fully excavated, secured, and cleaned. In conventionally driven tunnels with no accessibility due to poor rock conditions, it is possible, but not recommended, to execute both mapping stages using only digital mapping on photogrammetry models that does not require physical presence in the tunnel.

In mechanically excavated tunnels and shaft it is not possible to gain access to the front. Thus, only detailed mapping will be carried out, well behind the TBM or bore machine or after the completion of the shaft.

An imperative requirement for the mapping to work is that the exposed rock surfaces are cleaned from debris and dirt (including the floor in the deposition tunnels) and remain uncovered by shotcrete or lining until all necessary data is gathered.

The level of detail captured in each mapping type is different both for fracturing and delineation of rock types. The RoCS method description (#5 in Table 3-1) explains details required for each mapping type. As an example, a fracture trace length cut-off corresponding to ≥ 3 m is suggested for the overview mapping, whereas for detailed mapping a standard cut-off length is suggested to ≥ 1 m. The trace length cut-off values are defined based on the expected fracture size distribution at the repository depth in Forsmark (cf Fox et al. 2007), the possible impact on the tunnel stability and mapping experiences from the Äspö HRL. However, these standard values may be revised in the future depending on needs relative to available time. Fractures shorter than 1 m in size could, for example, be included locally in dedicated campaigns, as input to DFN modelling, as well as for characterization of deformation zones and possible excavation damage zones.

Geophysical methods (#10–12 in Table 3-1) can be used as a complement to the routine investigations, described in Section 3.2, to support identification of potentially critical structures. Cross-hole and cross-tunnel methods can be evaluated especially in the deposition tunnels, as support to other investigations.

3.2 Planned investigations for different stages

The application of the different investigations varies depending on the stage of repository construction and differences in excavation methods. The geological investigations during the excavation of accesses (ramp and shafts) and the central area will focus on constructability and to identify layout defining structures, whereas investigations in the deposition areas will need to be more detailed to identify potentially critical structures and rock mass with unfavourable thermal conditions (see Section 3.3).

The current plan by SKB is to use different excavation methods for different parts of the repository as follows:

- TBM for the access ramp.
- Raise-boring for the shafts.
- Conventional techniques for the central area and transport tunnels.
- Mechanical excavation for deposition tunnels.
- Boring for deposition holes.

Depending on excavation method the deployment of investigations will have to be adapted as illustrated in Table 3-2. Investigations based on pilot boreholes in front of a tunnel, shaft or deposition hole can be executed regardless of excavation method.

Generally, all mechanical excavation methods (TBM, boring, mobile miners) prohibit direct access to the excavation front, which limits the availability to execute mapping activities of the rock face. Thus, for these methods all rock mapping will need to be carried out behind the excavation equipment (ramp, deposition tunnels) or after completion (shafts and deposition holes). For tunnels excavated with conventional techniques, mapping can readily be executed at the tunnel front after each blasting round.

The intent with routine investigations is that they should comprise part of the construction process. Generally, routines should follow the same overall pattern in all facility parts, depending on excavation method. The routines need to be practiced and fine-tuned in consultation with the contractor during the whole construction process. It is important that data are captured consistently during construction, although the possibility to access may vary depending on rock stability and groundwater inflow. Access to information from pilot boreholes may also be more selective for the ramp and shafts but expected to be gathered routinely in the deposition areas.

Table 3-2. Planned routine investigations at different stages.

Excavation method	Probe hole measurements	Pilot hole investigations	Overview tunnel mapping	Detailed tunnel mapping
TBM in access ramp		X*		X
Raise-boring of shafts		X*		X
Conventional drill and blast in central area (caverns) and main/transport tunnels, nisches	X	X*	X	X
Mechanical excavation of deposition tunnels		X		X
Boring of deposition holes		X		X

* If available.

3.2.1 Routine investigations in areas using conventional excavation methods

An overview of a typical operating cycle for areas using conventional excavation by drill-and-blast (central area, main/transport tunnels, nisches) contain routine investigations as presented in Figure 3-1:

1. Core drilled pilot boreholes, if available. The pilot boreholes are investigated by a standardized multidisciplinary programme, similar to those conducted during the preceding surface-based characterizations, which includes TV logging (OPTV), detailed geological mapping by using the Boremap system and conventional geophysical and hydrogeological logging.
2. Percussion (top hammer) drilled probe holes. Mainly provides hydraulic data to assess the need and extent of grouting for the next 4–5 blasting rounds (i.e. approximately 20–25 m).
3. Overview geological tunnel mapping of the latest blasting round.
4. Detailed geological tunnel mapping.

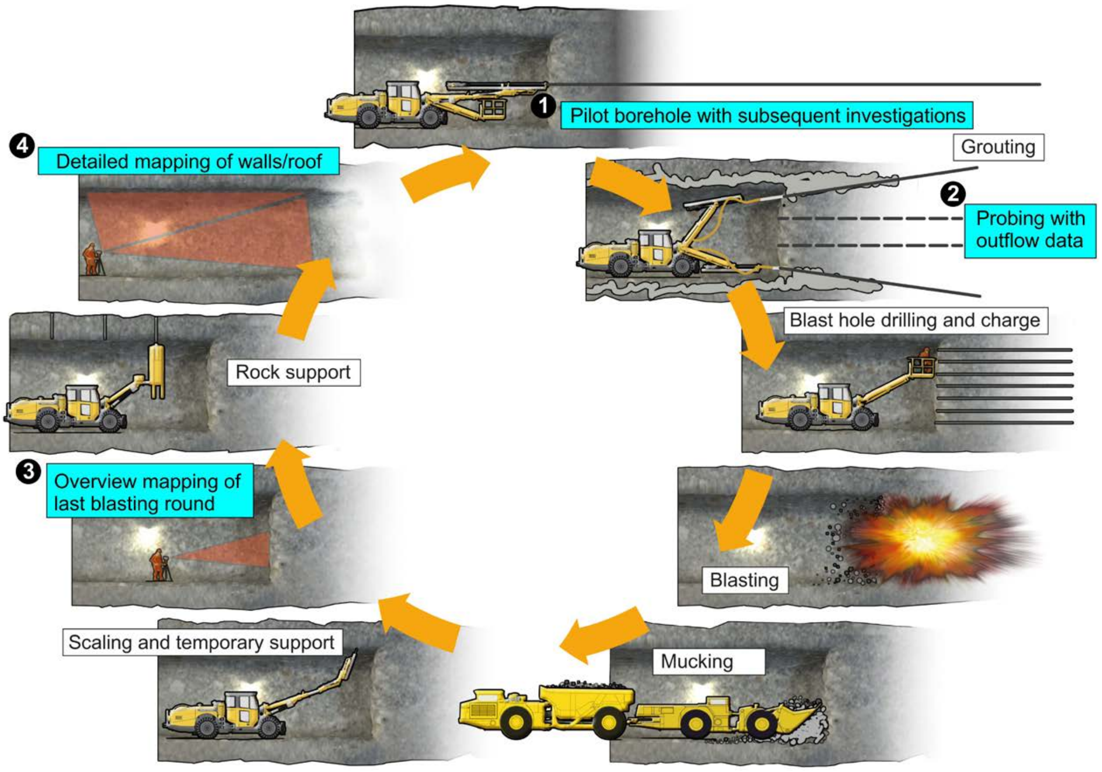


Figure 3-1. Schematic illustration of the routine operating cycle for tunnel excavation by drill-and-blast in the repository area, showing the investigation sequence with pilot and probe hole drilling, borehole investigations, excavation and overview tunnel mapping followed by detailed tunnel mapping. Modified from SKB (2010).

3.2.2 Routine investigations in areas using mechanical excavation types TBM, boring and raiseboring

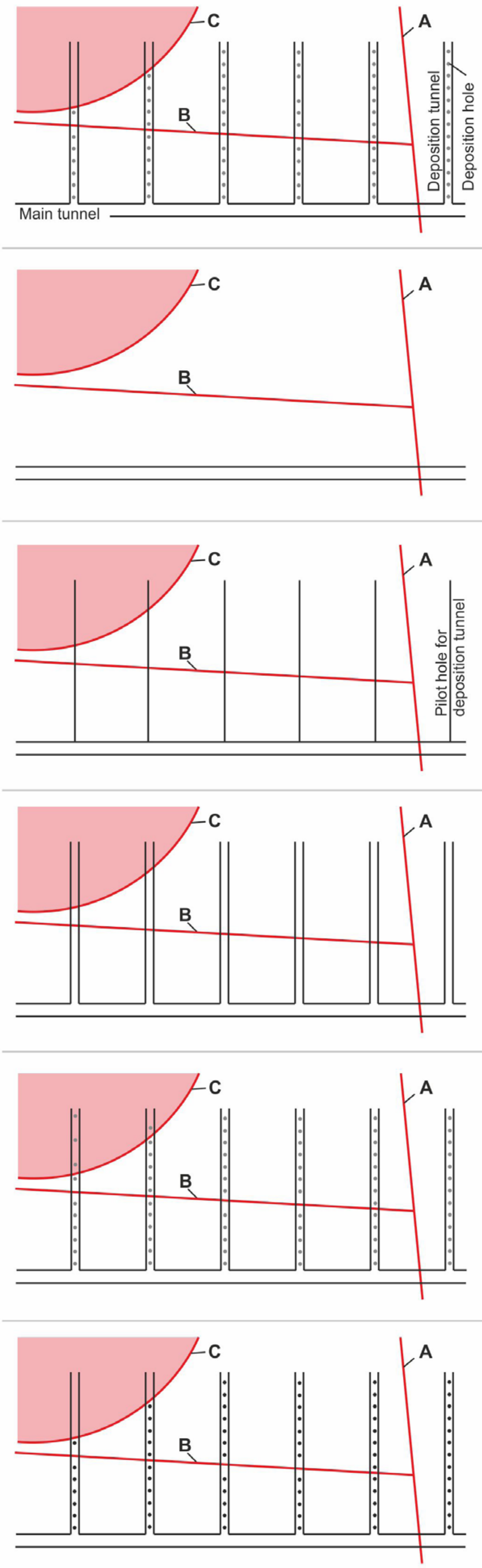
An overview of the typical routine investigations in mechanically excavated tunnels differs from conventional excavation as it is not possible to perform geological mapping at the front of the tunnel (or shaft). Thus, in areas using mechanical excavations (deposition tunnels, deposition holes, ramp and shafts), the investigations include the following steps of routine data capture:

1. Core drilled pilot boreholes, if available. The pilot boreholes are investigated by a standardized multidisciplinary programme, similar to that conducted during the preceding surface-based characterizations, which includes TV logging (OPTV), detailed geological mapping by using the Boremap system and conventional geophysical and hydrogeological logging.
2. Detailed geological tunnel mapping.

3.3 Investigation strategies to support identification of potentially critical structures and volumes

Major layout decisions in the deposition areas requires identification of potentially critical structures and rock volumes with low thermal conductivity, along with critical properties of the rock mass with bearing on the performance of the buffer, backfill and canister. The general approach to identify such features in a deposition area is illustrated in Figure 3-2. The actual investigation strategies to be used can be found in the detailed site investigation programme (SKB 2018).

The exact strategy, setup and process flow are largely dependent on the site-specific conditions, and therefore part of the learning process during the preceding excavation of the accesses and central area, with further input from tests in the initial deposition tunnels.



Explanations

The diagram shows examples of potential critical structures and their intersections of deposition tunnels and planned canister positions. A and B dip steep to moderately and can disqualify canister positions. C is sub-horizontal and intersect 5 or more canister positions.

a) Construction of main tunnel

The main tunnel is preceded by a pilot borehole in which investigations can indicate A. In probe holes, water-conducting sections can be indicated (A). Tunnel mapping shows FPIs, their properties and water inflow (A). Tunnel geophysics may indicate the extistence of B. Integrative interpretation and subsequent modelling give a basis for decision of orientation and location of deposition tunnels.

b) Drilling of pilot holes for deposition tunnels

Potential critical structures can be detected by investigations in the pilot boreholes (B); their approximate size is determined by correlation between geological borehole data, with support from hydrogeological measurements (B). Integrative interpretation and subsequent modelling gives a basis for decision on whether a deposition tunnel should be built or not.

c) Construction of deposition tunnels

Probe hole drilling gives the water inflow. Geological tunnel mapping shows B as FPI, its properties and inflow. Orientation and possible extent of A and existence of C may be indicated by tunnel geophysics and tomographic processing. Integrative interpretation and updating of models provides a basis for preliminary placement of canister positions.

d) Drilling of pilot holes for deposition holes

Pilot hole drilling is avoided in positions where potential critical structures have been detected from the deposition tunnel. Confident detection of C requires drilling of some pilot holes. Geological mapping, with support from geophysics and hydrogeological surveys, reveal details in the distribution of thermally anomalous rock types and properties of potential critical structures. Integrative single-hole interpretations serve as a basis for a renewed updating of models, which in turn are used to decide whether a deposition hole should be drilled or not.

e) Drilling of deposition holes

The exemplified objects have been identified in the preceding steps and virtually all potential critical structures can be avoided at these positions. Geological mapping, tunnel geophysics and inflow measurements will be used as a basis for integrative interpretation. An additional model update will be made to clarify whether the holes can be approved or if some have to be rejected.

***Figure 3-2**. Schematic illustration of the relationship between the excavation/investigation sequence and the identification of critical structures during a tunnelling campaign in a deposition area. Modified from SKB (2010).*

4 Integrative and multidisciplinary interpretation

The primary data stored in SICADA need to be further integrated and synthesised before they can be used in deterministic geometrical modelling. The process of data integration and synthesis implies combination of results of different methods to give the best estimate of the geometry and properties for a particular feature within the model volume; in other words, it is a method to sift out data of relevance for the deterministic modelling. Integrative interpretation can be regarded as an intermediate step of synthesising the geological data, with support from hydrogeology and geophysics, before the subsequent 3D deterministic modelling work. The basic idea is that the interpretation will result in a joint platform from which all subsequent 3D deterministic modelling emanates. As a joint communication tool between the different disciplines, it is emphasized that specialists of hydrogeochemistry and rock mechanics participate in the process, even if no such data are considered in the interpretation.

The interpretation process plays an important role in the efforts of multidisciplinary integration by giving individuals involved in the investigations and/or modelling work the opportunity to influence the interpretation process. The interpretation result should be the output from collaborative work from multiple experts. Another valuable aspect is the joint examination of available data and calibration/normalization amongst the individuals of the modelling team. This also allows tackling potential uncertainties in the interpretations in a more comprehensive manner.

During the construction of the repository there are mainly two types of multidisciplinary geo-scientific activities needed in the geological modelling process: geoscientific single-hole interpretation (GSHI) and geological single-tunnel interpretation (STI). Both are performed with the purpose of parameterizing the geological conditions to

1. rock units (RU), and
2. borehole/tunnel deformation zones (BDZ/TDZ).

These building blocks, as defined under Section 1.5, form the basis for the subsequent 3D deterministic modelling and consists of identified sections of different bedrock conditions along individual boreholes (GSHI) and along each individual tunnel or shaft in the repository (STI). The interpretation products are stored in SICADA. Complete descriptions of the methodologies are presented in Appendices 2 and 3, respectively.

It must be kept in mind that the integrative interpretation procedures outlined here are based more on expert judgement, skills and experience of the individuals in the modelling team rather than on automatic or semi-automatic processing of primary data sets.

The GSHI and STI are completed independently, without influence of existing 3D models or time-dependent data (e.g. changes in the rock stress situation or any change in hydraulic conditions due to the repository construction). Thus, the basic principle is that the interpreted rock units and deformation zones generally remain fixed *regardless of later correlations established during the 3D deterministic modelling*. This approach of independence from the modelling gives full traceability during multiple steps of model changes. However, the results of the interpretations may be subject to revision if *new data, or knowledge*, is acquired. Such revisions can, for example, include addition of new borehole or tunnel deformation zones, changed confidence levels or more detailed geometrical divisions.

Interpretation processes that fall under the collective name multi-hole/tunnel interpretations, which include cross-hole, cross-tunnel and hole-to-tunnel correlation based mainly on hydrogeological testing and geophysical surveys, are part of the subsequent step of 3D deterministic modelling.

4.1 Geoscientific single-hole interpretation (GSHI)

GSHI is the methodology to interpret a single borehole. Two types of GSHI are planned:

- Overview GSHI – used as the principal input to an update of the geotechnical baseline report in support of engineering-related decisions
- Detailed GSHI – used as the key link between primary data and the modelling work, by way of a multidisciplinary synthesis of geological data with support from geophysical and hydrogeological information in a borehole.

The methodology was originally developed for use in the site descriptive modelling, concluding the surface-based site investigations, with a released last version of the method description in 2006[5]. The methodology is focused only on cored boreholes and is presented in detail in Appendix 2.

The overview GSHI focuses on identifying only brittle structures, which may have possible implications for the stability of, and water inflow to a planned tunnel. To provide this information, the overview GSHI aims only at the identification of sections of increased brittle deformation, which are denoted borehole fracture zones (BFZ) to separate the nomenclature from the more comprehensive identification of deformation zones made in the detailed GSHI, see Table 1-1.

The objective of the detailed GSHI is to identify and quantify/describe borehole deformation zones (BDZ) and rock units (RU) that intersects the borehole, which are the smallest geological entities that *can* be associated with (1) structures defined as potentially critical for seismic reactivation (cf Section 5.4.1) and (2) volumes of possible relevance for the thermal modelling (cf Section 5.5). Identification of a potentially critical structure in a single borehole, requires understanding of the site conditions in Forsmark as well as an understanding of the character of such zones. As explained in Section 2.3, criticality of a structure is related to the size of a zone. However, size cannot be observed directly in a borehole but needs to be subjectively interpreted from what can be seen along the borehole, as further explained in Section 5.6.

The identification of BDZ and RU is conducted in two steps; (1) a desktop assessment where geologists, geophysicists and hydrogeologists work separately to generate discipline-specific data for the next interpretation step (2) which is a multidisciplinary evaluation where interpretations of BDZs and RUs are mutually agreed. The general process of the detailed GSHI and the data used are shown in an overview flowchart in Figure 4-1. Flowchart showing the steps in the detailed GSHI procedure for the identification of rock units and borehole deformation zones.. For BDZs identified with high confidence, a further kinematical analysis is executed to give further support to the 3D deterministic modelling as explained in Appendix 2.

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[5] Metodbeskrivning för geologisk enhålstolkning, SKB MD 810.003.

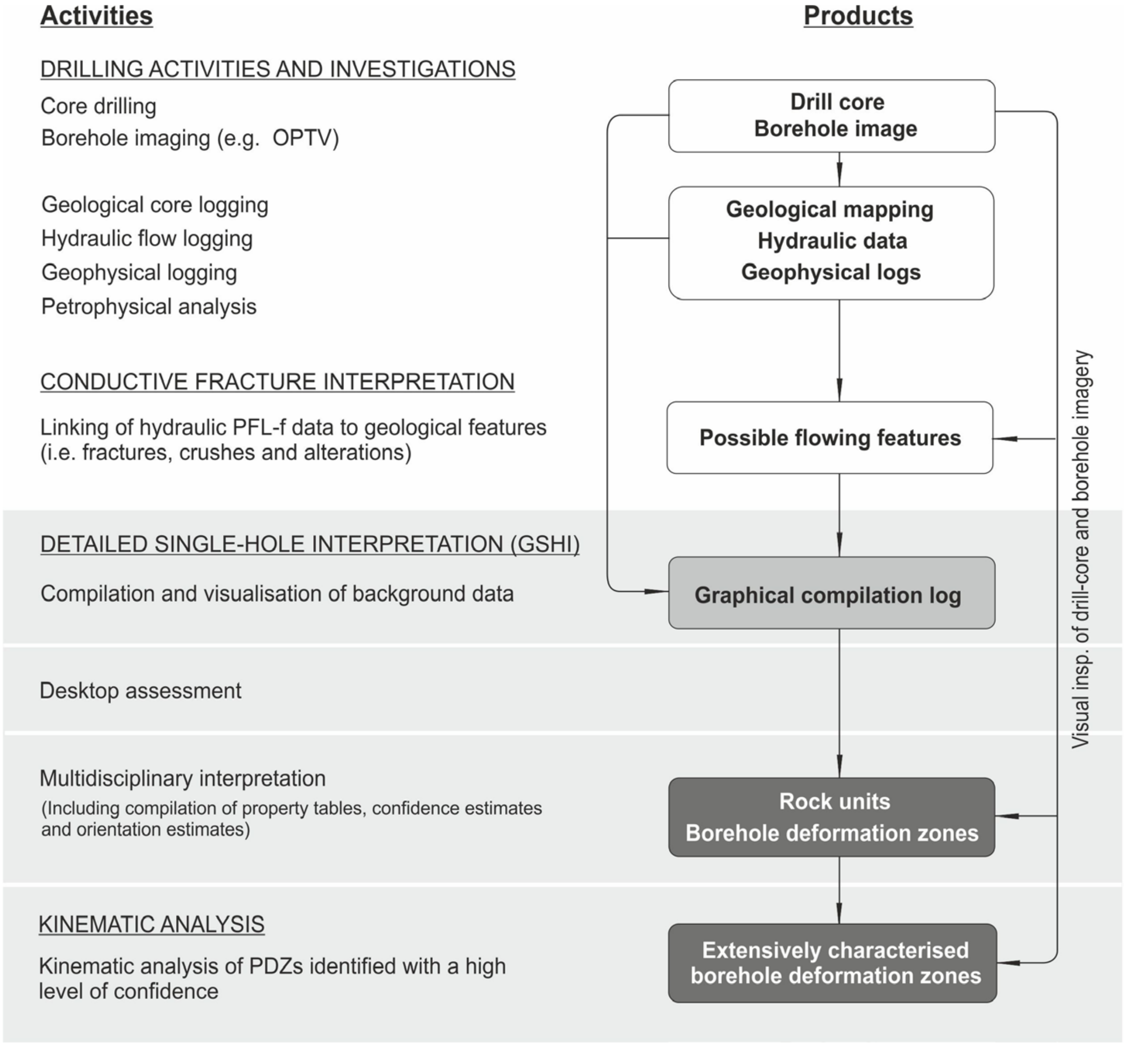


Figure 4-1. *Flowchart showing the steps in the detailed GSHI procedure for the identification of rock units and borehole deformation zones.*

4.2 Geologic single-tunnel interpretation (STI)

During the repository construction phase most of the geological information will be acquired from tunnels, shafts and other underground openings. Compared to a borehole, an underground opening has a larger spatial extent and areal exposure that allows acquisition of detailed three-dimensional geoscientific information. Tunnel or shaft data can be simplified to building blocks, similar to GSHI, through an integrative interpretation of tunnel data. This process is called geologic single-tunnel interpretation (STI) and is explained in detail in Appendix 3. In addition to tunnel data, the STI can be supported with information from nearby pilot boreholes (with its GSHI), probe holes or geophysics, where such are available.

The STI methodology aims to identify and describe TDZ and RU that intersects the tunnel, which are the smallest geological entities that *can* be associated with (1) structures defined as potentially critical for seismic reactivation (cf Section 5.4.1) and (2) volumes of possible relevance for the thermal modelling (cf Section 5.5). The identification process is complex and requires a combined evaluation of key properties closely linked to deformation zone size, including mechanical instability and RUs with unfavourable thermal properties. The primary component in identifying TDZs is evaluating FPI structures identified during the RoCS tunnel mapping (cf Section 3.1.2). Even if the FPI criterion (Munier 2006) provides a feasible method of detecting critical structures, also smaller structures may need to be included as illustrated in Figure 4-2 and explained further in Appendix 3.

The interpretation procedure is largely similar to the GSHI, and can be separated into four steps:

1. Compilation and visualization of necessary data.
2. Desktop assessment.
3. Multidisciplinary interpretation.
4. Tunnel visit by the interpretation team for examination and a more detailed characterization of kinematic indicators.

The outcome of the STI is a geometry and a property description of each individual RU and TDZ.

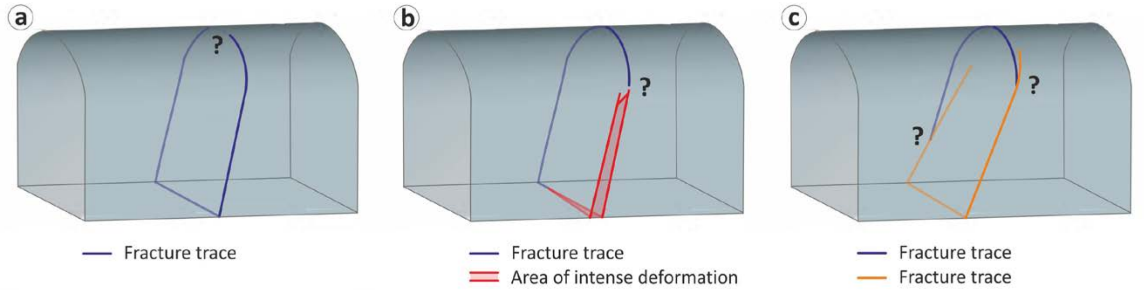


Figure 4-2. *Examples of FPI candidates that might escape detection during the geological tunnel mapping: (a) Fracture trace with a mapped break which might be attributed to cut effects or shadows, (b) an area of intense deformation that appears to continue as a fracture trace, and (c) fracture traces that appear to splay into or truncate each other.*

The initial two steps of visualization and desktop assessment are more comprehensive than for the GSHI, considering the amount of available data for a particular tunnel section, which also may involve pilot and probe/grouting boreholes and geophysics. A major advantage with pilot boreholes is that they can provide even further evidence and support to the identification of TDZs based on tunnel to borehole correlations.

In the third step, all disciplines carry out an integrated interpretation of RUs and TDZs established mainly from lithology and fracture data, with support from geophysics and hydrogeological data. It is important that this exercise also utilizes conceptual understanding in the analysis.

Finally, the fourth step is a verification by a visual inspection of the tunnel if the rock surface is still exposed after rock reinforcement. Possible modifications after the inspection can, for example, include updates in the interpretation or extent of a structure. To support further 3D modelling, this step should also include an assessment of kinematic indicators for any identified TDZ as explained in Appendix 3.

An overview flow chart of the methodology, including base data and related activities, is presented in Figure 4-3.

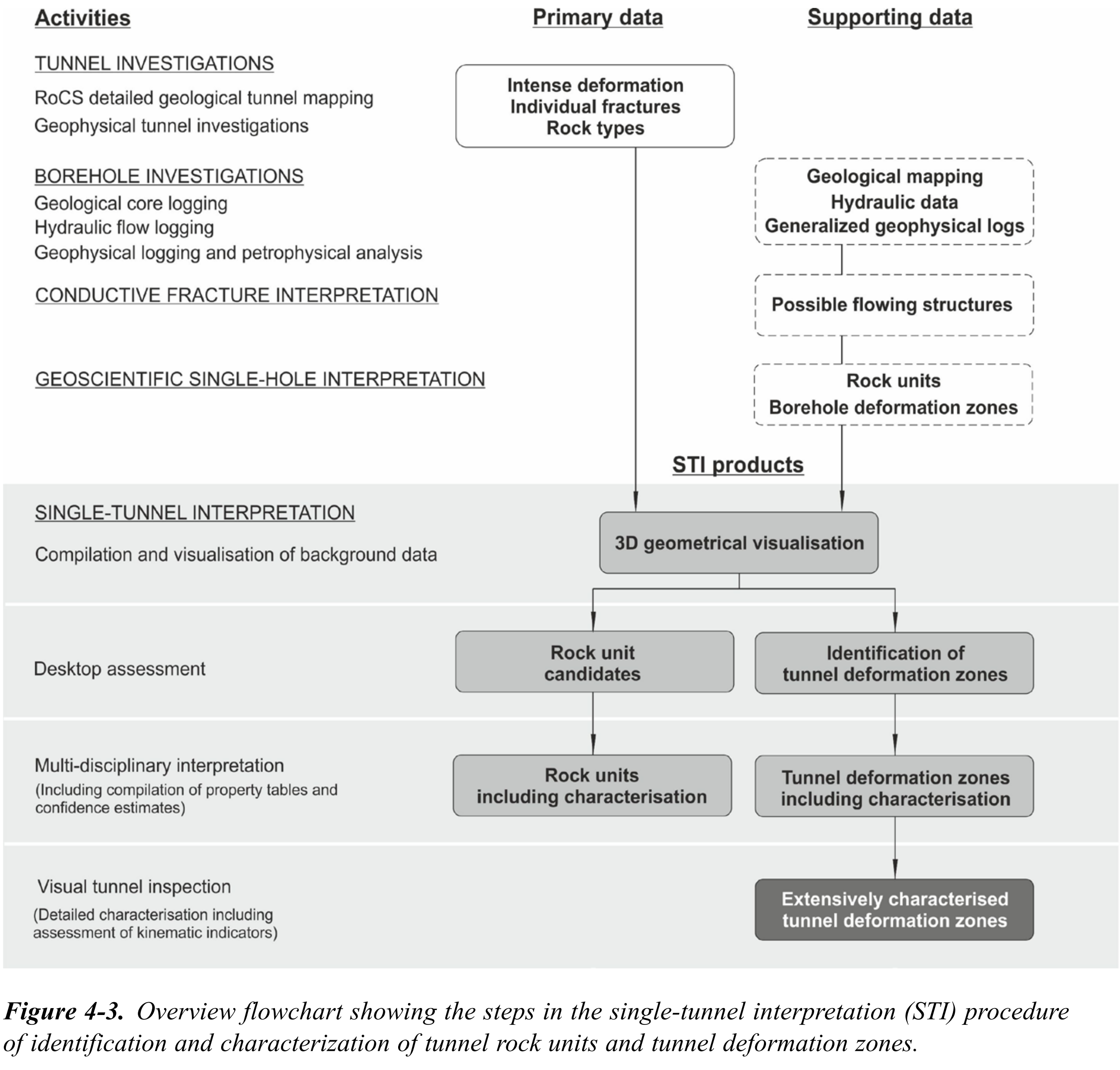


***Figure 4-3.** Overview flowchart showing the steps in the single-tunnel interpretation (STI) procedure of identification and characterization of tunnel rock units and tunnel deformation zones.*

5 Methodology for geological modelling

The methodology to develop geological models revolves around an iterative process of using interrelated interpretations and data from a multitude of surface-based and underground sources of information combined with the underlying conceptual understanding of the site. As described in Chapters 3 and 4, there are several stages of interpretation of primary data that precedes the construction of the geological 3D model, also involving support from other geoscientific disciplines – hydrogeology and geophysics in particular. The multidisciplinary interpretations involving boreholes and tunnels, i.e. GSHI (Section 4.1) and the STI (Section 4.2), are largely independent interpretations. The modelling methodology combines these interpretations with support from other sources of data and the conceptual understanding of the site into 3D geological models.

This chapter describes how a detailed 3D geological model of the rock mass is developed for the Forsmark site. The starting point for the development is the experiences and practices employed during the development of the SDM-site 3D geological model (Stephens and Simeonov 2015). This model was established on the surface-based site investigations, and derived by employing the original strategy and framework developed by Munier et al. (2003). Although the new methodology is designed to capture the specific situation experienced in Forsmark, it is applicable to other sites with similar types of underlying primary data.

5.1 General process for 3D geological modelling

During the surface-based site investigation stage for the Forsmark repository, the 3D geological models have been based on surface data, supported by a limited set of boreholes through the target volume down to and below repository depth, as defined in Stephens et al. (2007). To maintain the integrity of the repository and limit potential hydraulic pathways to the biosphere, there are restrictions on the amount of drilling that can be made from the surface. Also, the geological conditions in Forsmark with a crystalline bedrock that shows increased fracturing near the surface is not particularly suitable for detailed seismic evaluations. Instead, the 3D modelling relied to a large extent on projecting the observed pattern of surface structures down to repository depth, supported by confirmation of their existence with selective drillings.

In this report, the modelling methodology is developed for the detailed site investigations to be employed during the planned underground constructions at Forsmark. The methodology is similar to that previously presented by Munier et al. (2003) but with the addition of techniques and processes for 3D modelling by:

- Using underground observations of geological objects not necessarily extending to the ground surface.
- Identifying structures and rock units to a finer level of detail.
- Allowing several individuals of the modelling team working in parallel employing a common 3D geological object library.
- Addressing uncertainty through utilizing conditioned stochastic simulation of the spatial extent of deterministic objects as well as quantifying uncertainties in geometric interpretation and the object properties.
- Providing continuous improvement of the site understanding as support for rock mechanical and hydrogeological modelling.
- Providing support to the design and construction of the repository.

The methodology of deriving the geometry and properties of a modelled geological object follows the process described in Figure 5-1. This general flow chart illustrates the process of evaluating the GSHI, STI, geophysics and hydraulic tests to be used in the successive improvement of the 3D geological models with support from the conceptual understanding of the geological processes.

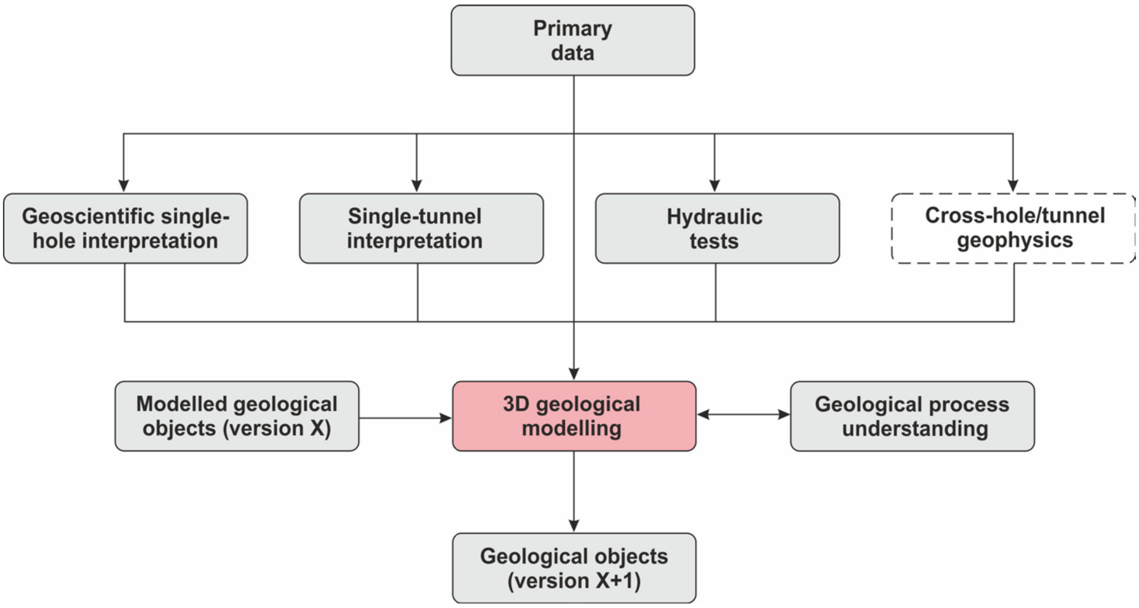


Figure 5-1. *Overview flowchart showing the main building blocks of data and interpretations used in the 3D geological modelling. Cross-hole/tunnel geophysics is an optional investigation.*

5.2 Object-based geological modelling

A successful 3D geological model describes the subsurface as clearly and simply as possible – for its intended purpose. Zobl and Marchallinger (2008) proposed a method for extending relatively simple building information models (BIM) into the subsurface by incorporating the surrounding natural environment. This method enabled the management of subsurface construction information along with all geo-related (subsurface) data, such as geological, hydrogeological and geotechnical objects and properties using CAD based solid modelling and relational databases.

The methodology presented here builds on similar concepts but is based on 3D geological models that are closely tied to a spatial database, in which each object is handled separately whilst retaining its spatial relation with the surrounding environment, as also proposed by Brodaric and Hastings (2002) and Breunig and Zlatanova (2011).

There are essentially two main groups of objects that will populate the geological model: (1) volume objects consisting of rock units, rock domains and fracture domains, and (2) surfaces, or relatively thin, sub-planar deformation zone objects.

Volume objects of the same type (such as rock domains) should create a model volume where all points in space are described by objects, i.e. being “space filling” as prescribed by (Munier et al. 2003). In contrast to these volumetric objects, deformation zones are objects with very limited thickness compared with their length. Although the two groups are geologically interrelated, from a computer model perspective the deformation zone objects are only overlaying the volume objects, thus not creating complex geometric intersections of the volumes.

5.2.1 Concept of a geological object library

Object-based geological modelling methodology is new in the sense that all *geological features* that are interpreted and modelled over a site are treated as individual objects with specified relations to their surroundings. These relations are, apart from their defined geometric extents, also definitions of their interaction with other objects such as terminations or constraints in extents, e.g. against neighbouring objects (geological or engineered objects such as tunnels and boreholes) or the common sharing of surfaces, such as boundaries between rock domains. The relations also include geometry constraints by interpreted data that occurs at intersections with the ground surface, or from interpreted constraints of other structures, boreholes or tunnels. Each object, with specified spatial relations, is stored in a separate object library.

A *model* constitutes the anticipated selection of objects extracted from the object library within a specified volume, as illustrated in Figure 1-6. This selection of objects has previously been stored within a single model file in RVS, and similar techniques are used in many commercially available geological modelling tools. The disadvantage with this prevailing approach has been that the modelled objects are contained in a single computer file. The model is also often developed for a specific purpose over a specific volume. The approach during SDM-Site was to have one modeller that was responsible for executing all changes to one model file as new data became available.

By introducing a common object library, the following can be achieved:

- Secure version handling of geological objects.
- Full traceability of object creator and editor.
- Multiple individuals of the modelling team working simultaneously in multiple areas/volumes of the repository whilst maintaining the integrity of modelled geological objects.
- Access to the most recent version of the modelled objects at the site regardless of the modeller/user.
- Retaining the possibility of being independent of which modelling tools to use over time. This increases the flexibility for SKB to adopt and use the best suited modelling tools on the market over time.
- A common object library could also allow regulatory authorities to review the progress of interpretations and models during the development of the repository.

5.2.2 Object handling in the library

For practical reasons a geological object library should only encompass objects within with a specified maximal volume, which encompasses all geological modelling activities at the site. A geological model volume was developed in Forsmark during SDM-Site (cf SKB 2008) covering both planned repository constructions at the Forsmark site. This volume will be used as the initial maximum extent within which all sub-sequent model volumes can exist (see Section 2.1.1). If the investigation or modelling volume increases for some reason, the maximum extent can be extended.

The process of entering objects into the library is illustrated in Figure 5-2. Each geometric object is stored in the object library with a unique identifier, object type, version number and details of the creator/editor. The data components should at a minimum consists of (a) object type, (b) geometry and (c) spatial constraints and relations to other objects. However, this information will only enable the geometric construction of the object. To understand what the geometry means, there is a need to complement with geological descriptions as illustrated in Figure 5-3. Geological descriptions should be added in a specified table format as presented in Appendix 4. Parts of this table can be extracted from the geometric relations in the 3D modelling tool:

- Intercepts with boreholes or tunnels (section length for each borehole or tunnel).
- Average orientation, based on geometry (deformation zones).
- Horizontal length, based on geometry (deformation zones).
- Average measure of thickness (deformation zones).
- Volume, based on geometry (volumetric objects RFM, FFM).
- Modelled geometric constraints including relations to other objects.

Other parts of the geological descriptions need to be analysed and summarized from the source data: Averaged geological properties for the object (see Appendix 4) and stereographic projections, if applicable. Also, description of the modelling procedure, assumptions, uncertainties, conceptualisation decisions and confidence estimates (see Section 6 and Appendix 4) need to be manually added.

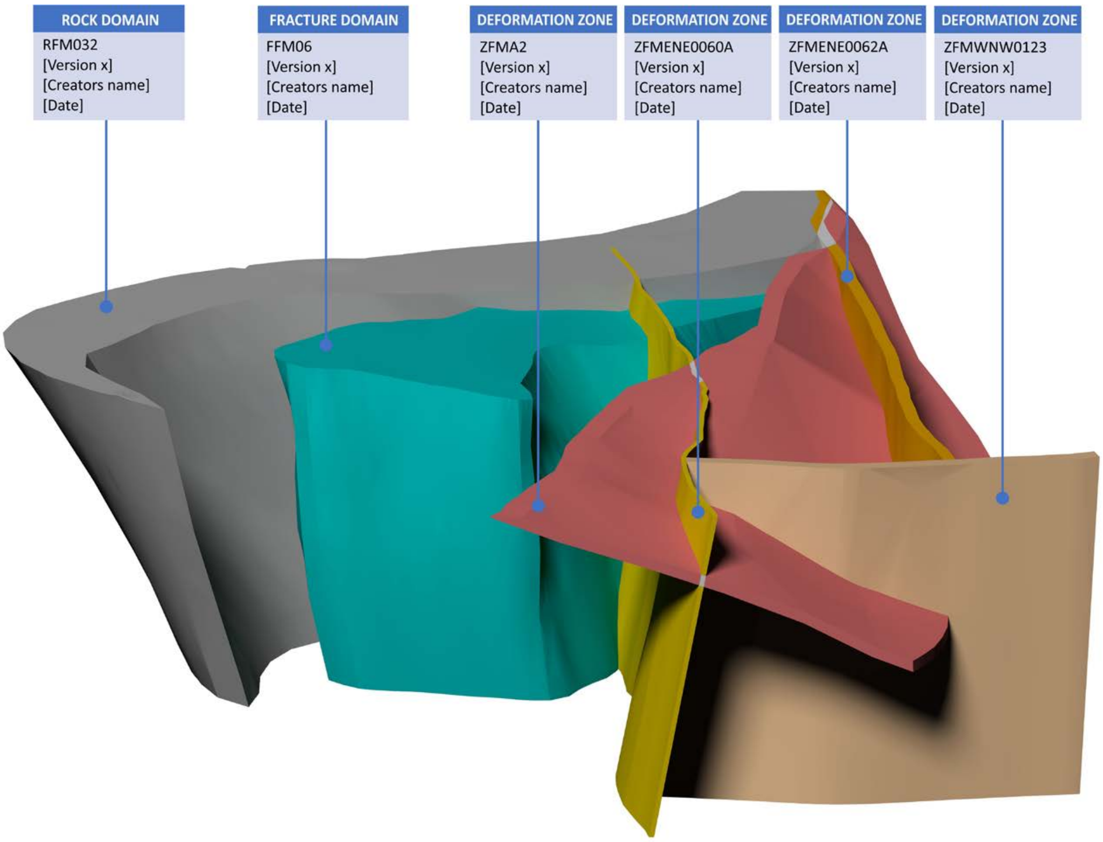


Figure 5-2. *Example of geological object geometry and the identity descriptors necessary for entering the object into the geometry library.*

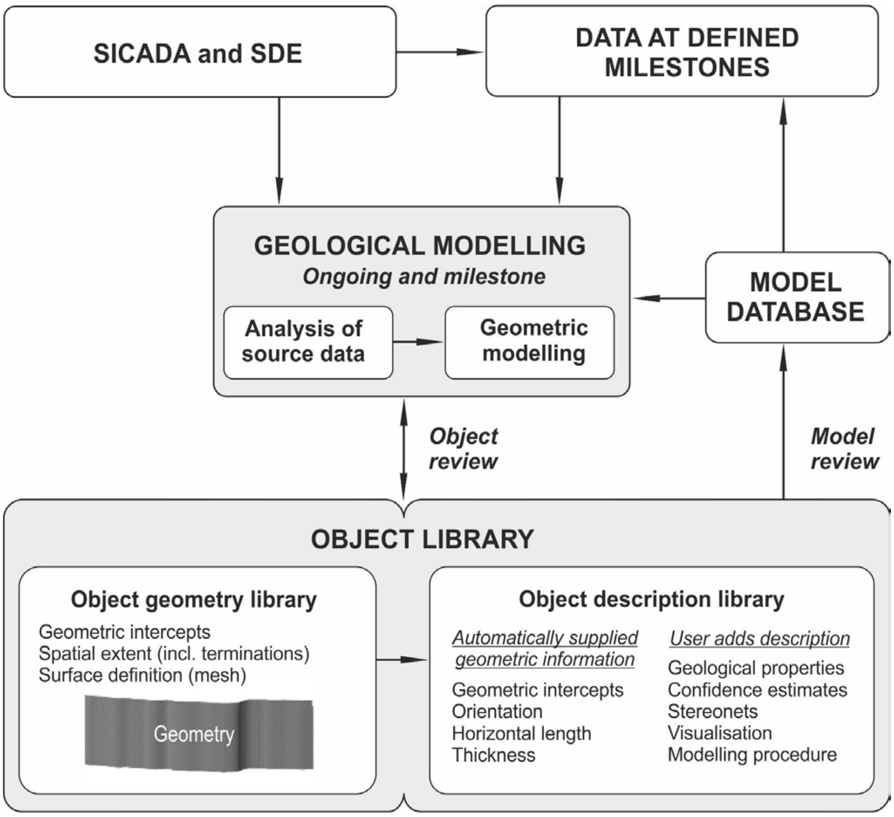


Figure 5-3. *Flow chart describing the geometric and descriptive parts of the geological object library and its relations to the modelling process. Details regarding source data are presented in Figure 1-3.*

Handling of newly created or edited object versions can be made according to the following convention:

- Each update of the geometry results in a new version number (e.g. version 1, 2, 3…).
- Updates to the geological object descriptions (D) receives a new version number Dx (1, 2, 3…) according to the format [Geometry version].Dx.
- The geological object description version number is independent from the geometry version number. For example, an object geometry that is updated from version 2 to 3 may not have any change in the version of the geological description. The version numbers could go from, for example version 2.D8 to 3.D8, where the first number change reflects a change in geometry and the second number reflects an unchanged geological object description.

Figure 5-4 illustrates the iterative process of querying the object library for objects that can be copied into a defined model volume, adding new data, updating and/or adding new objects, which can then be uploaded again to the object library.

A systematic construction of the geometric objects guarantees backward traceability of earlier object versions and ensures that comparisons can be made between different object interpretation alternatives. The iterative modelling process is described in Figure 5-4 and can be summarized as follows:

1. The volume of interest needs to be defined using a collectively decided coordinate system, currently SWEREF 99 18 00/RH 2000 for the Forsmark site. Alternatively, specified standard, pre-set model volumes can be used for defined working areas within the repository, cf sequence A in Figure 5-4. Several model volumes can co-exist at the same time as well as overlap as illustrated in Figure 5-5.
2. As the volume is created, a query is made to the spatial database to load objects that exists within the volume or within a defined proximity to the volume or to object(-s) of interest, cf sequence B in Figure 5-4. The user can decide whether to include or exclude individual objects depending on the purpose of the modelling, cf sequence C in Figure 5-4.
3. Include interpreted products such as GSHIs and STIs to the geological model volume which can be supported by primary data from SICADA/SDE and background models from SKBmod, cf sequence D in Figure 5-4.
4. Based on the conceptual understanding of the site, the uploaded data and existing objects from the spatial database, a geometry for the object is modelled using the process described in Section 5.4.
5. During the modelling exercise, new objects can be created, existing objects can be edited or deleted, and geometric relationships between objects can be changed. Deleted object versions should be possible to retrieve such that older models can be recreated.
6. After the geometry has been created each object is assigned an appropriate geological type.
7. Once the geometry is created, evaluated geological characteristics and the basis for interpretation of the object should be entered in the descriptive documentation of the object, as described in Appendix 4. The descriptive documentation shall always be uniquely linked to the object geometry in the object library.
8. After completion of the modelling exercise, the user can either upload new or edited objects to the object library, cf sequence E in Figure 5-4 and also save a copy of the model to SKBmod, cf Section 5.3.
9. All other users that are working in model volumes located nearby and are affected by the updates of the current objects are notified when updates occur in the object library and should be able to download updated versions to their own model volume. In case two modellers are working on the same object, an authority matrix delineating who has the mandate to the object library is necessary, to enable review and quality control of the modelling activities (see review process described in Appendix 5).

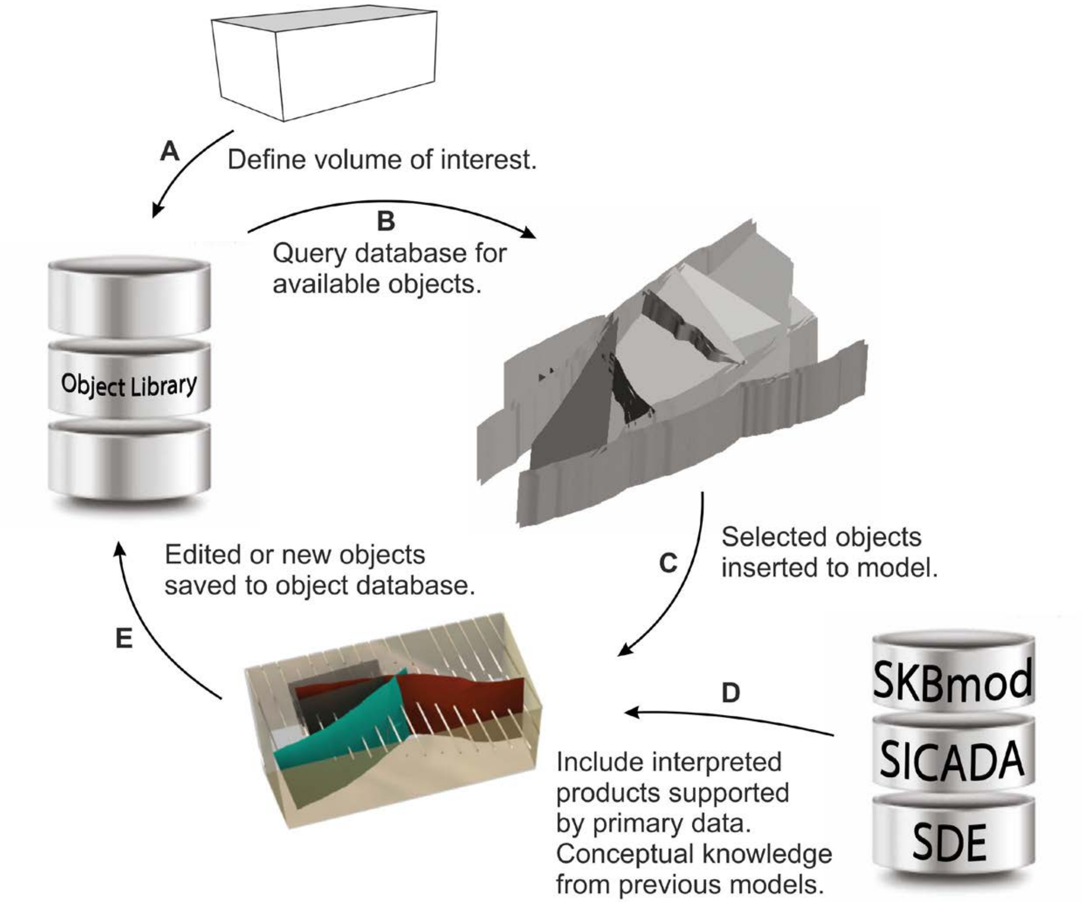


Figure 5-4. *Process visualization of querying for, creating or editing and re-entering objects to the object library. For details of SKBmod, see Section 5.3.*

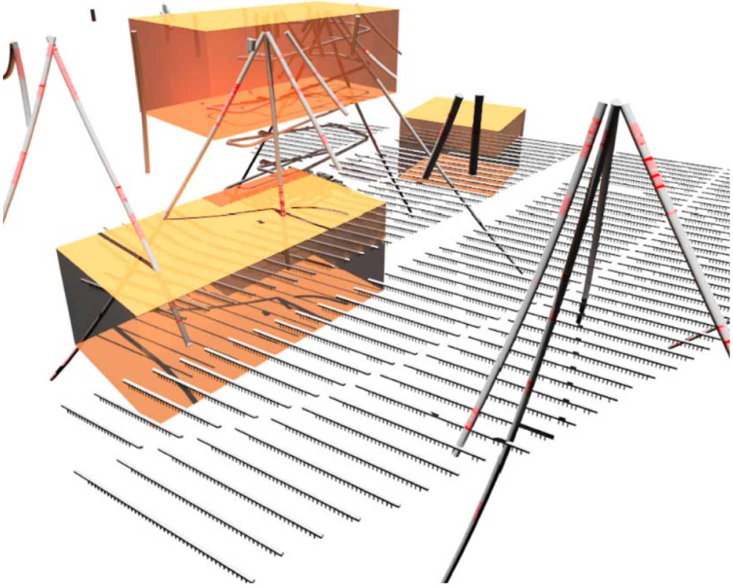


Figure 5-5. *Illustration of model volumes that can exist in different shapes and sizes simultaneously in the rock volume hosting the repository. Model volumes can also overlap.*

5.3 SKBMod – SKB's central model database

SKB has developed a central model database where officially reviewed models created at defined milestones shall be stored. This database hosts models from all geoscientific disciplines and is utilized to share models between disciplines.

During the geological modelling, as illustrated in Figure 5-3, the main output is focused around creating and updating objects and storing them in the object library. This concept enables a secure platform for sharing preliminary geological models between individuals of the modelling team. On request from other disciplines (e.g. hydrogeology) preliminary models can be shared through SKBMod.

At modelling milestones, cf Figure 5-3, geological models are created based on specified data sets. These models are exported to SKBMod for use in downstream models and for reporting the current level of site understanding.

5.4 Process for modelling deterministic structures

This section describes the 3D modelling process for identifying and modelling deterministic structures. However, the strategy and sequencing of the various steps of modelling are described in the respective operational programs for the underground constructions at the Forsmark site.

5.4.1 What shall be identified and deterministically modelled?

Two types of structures shall be modelled deterministically: deformation zones with the potential to exceed a critical size of 200 m equivalent radius and sheet joints of inferred hydraulic importance.

Considering the seismic-risk aspects, the minimum size for deterministic modelling of critical structures (CS) of Class 3 is given by the canister failure criterion, which with the most current canister design limits the maximum allowable slip along a structure to approximately 5 cm (SKB 2009a). In this context, the notion of "Critical radii" was introduced by Munier (2006) as a discriminator for the smallest radius for any given combination of fracture orientation and distance to fault that can host a single slip exceeding the canister shear failure threshold. Current estimates of critical radii for the Forsmark site are the result of more than a decade of comprehensive modelling by B. Fälth and his co-workers (e.g., Fälth et al. (2016) and references therein). The most important conclusions of these efforts are presented by Hökmark et al. (2019) and can, with due respect to assumptions and uncertainties, be summarized as follows:

- The only zone prone to reactivation in a reverse stress regime within the volume of the planned repository is the gently dipping ZFMA2, which is classified as CS2. All other known zones within the repository volume are inferred to be tectonically stable based on the notion of Coulomb Failure Stress (Harris 1998). The repository is planned in the footwall of ZFMA2, where the maximum induced displacements are generally significantly smaller than in the hanging wall. This means that the critical radii are generally much larger in the footwall.
- Horizontal to sub-horizontal, brittle structures could potentially host large slips and have consequently the smallest critical radii.

Hökmark et al. (2019) has calculated the minimum critical radii as a function of distance to ZFMA2 (Figure 5-6), based on the most conservative modelling case by Fälth et al. (2016). Within the repository volume, the smallest critical radii with values below 500 m (i.e. the cut-off size for deformation zones in the SDM local model volume) are restricted to FFM06 and the southernmost part of FFM01. A minimum critical radius of 215 m is given immediately south of the planned repository. For reasons of conservatism, this is assumed to be the minimum size that requires identification. Thus, all structures potentially exceeding a 200 m equivalent circular radius (or expressed as structures with a length along-strike of 400 m) need to be identified during the interpretation and subsequent modelling procedure. In practice, this means that these structures need to be identified already in the GSHI and STI steps, during which the basic modelling components are defined. By this approach, the preceding interpretative steps of the modelling process likely needs to include smaller deterministic objects that may have a size that is less than the critical size (i.e. 200 m equivalent circular radius). These structures are indeed not potentially critical but will nevertheless be stored in the object library as minor structures for possible future reassessment and as feedback for forthcoming interpretations of borehole/tunnel deformation zones and 3D modelling of deformation zones.

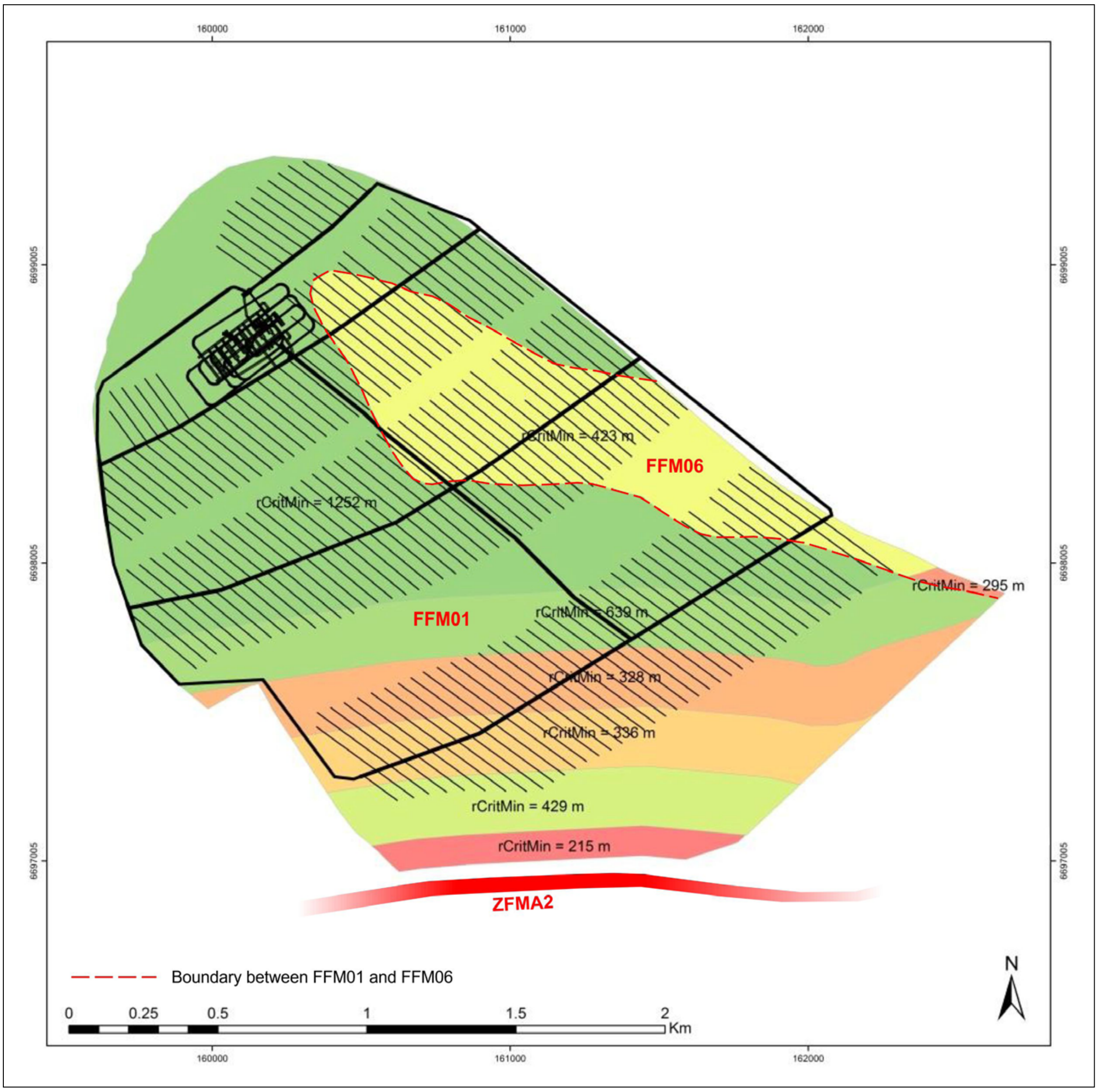


***Figure 5-6.** D2 repository layout relative to the minimum critical radii as a function of distance to ZFMA2. For each distance, the smallest radius from each set has been chosen. Modified from Hökmark et al. (2019).*

5.4.2 Site descriptive modelling based on ground-surface data

Surface lineaments are of geometrical importance for the modelling of steeply dipping to vertical zones, whereas seismic reflectors in surface data provides the basis for the modelling of gently dipping zones.

Three-dimensional geometries are obtained by matching lineaments and reflectors with borehole data where borehole deformation zones are identified during the GSHI, with support especially from fracture orientation data.

The along-strike truncation of steeply dipping to vertical zones is steered by the truncation pattern of the corresponding lineaments, which follows the conceptual understanding of the site (Stephens et al. 2007). In this manner, the zone length at the ground surface corresponds to the length of the matching lineament. Truncation at depth for zones that do not intersect other zones is carried out based on the assumption that the zone extends to a depth that is approximately the same as its trace length at the ground surface as illustrated in Figure 5-7. The consequences of these two assumptions are that:

- The along-strike length at depth is identical to that at the surface.
- Near vertical zones with an interpreted ground surface length that exceeds 400 m (i.e. the reference repository depth) are assumed to extend to the repository level.

The assumptions find some support in borehole data, but this argument could be considered as being circular in the sense that the same boreholes have been used for modelling of the zones. The assumption related to truncation at depth is potentially possible to evaluate during the excavations. Until such data are available, all surface-based modelling should be made according to the previously used geometry assumptions.

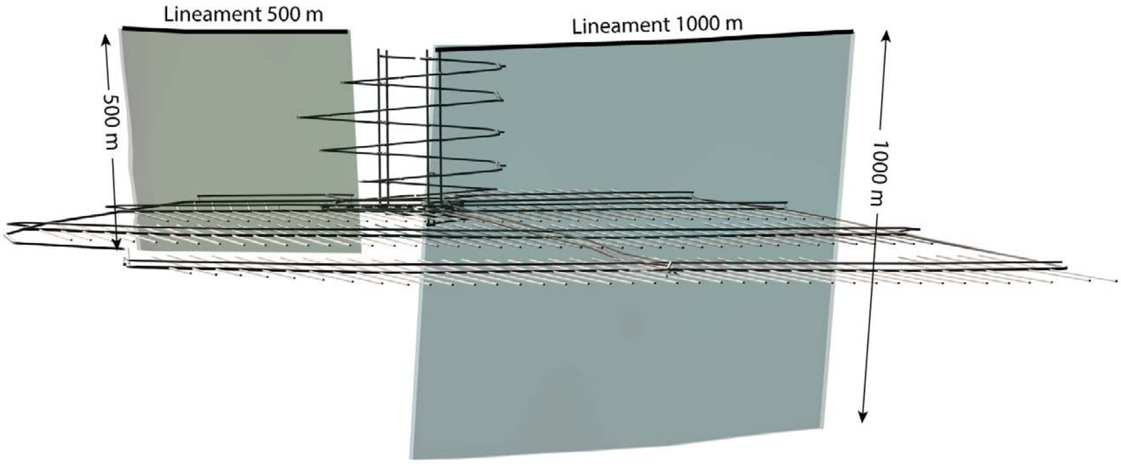


Figure 5-7. *Illustration showing two of the basic assumptions for the surface-based site descriptive modelling, where (1) the surface zone length corresponds to the length of the matching lineament and (2) that the zone extends to a depth that is the same as the surface trace length.*

5.4.3 Site descriptive modelling based on sub-surface data

New geological information will largely be acquired along the accesses, shafts and repository tunnels. A higher data density will exist in the immediate proximity to the underground openings of the repository. Few new boreholes are to be expected outside this volume.

At repository depth, it is less relevant to use surface-based lineaments as the geometric backbone for modelling steeply dipping to vertical zones. Subsurface modelling of structures only identified in underground openings and boreholes needs a new modelling approach. The ability to provide confident interpolation is therefore highly determined by the repository layout, where the deposition areas can be viewed as a horizontal slice of densely distributed investigation data. The information from the volume between the ground surface and repository level is assumed to be limited to the part of the volume where the ramp and shafts are located, supported by the limited existing surface-based drilling outside this area and possibly geophysics. With two horizontal cross-sections (the ground surface and the repository level) of dense and rather even data distribution separated by a much more sparsely informed volume, the variation in data density and resolution is comparable to an empty box as illustrated in Figure 5-8.

There are essentially three types of structures that need to be assessed at the repository level:

- Structures, previously identified in the SDM-Site model, modelled to extend from the ground surface down to repository level.
- Structures that are identified underground and may be possible to correlate to surface lineaments. With the current concept for ground surface-based modelling and accompanying assumptions, vertical zones with a length along-strike of 400 m or more at repository depth, may reach the surface.
- Structures that are identified underground but have no further source of information that allows well sustained extrapolation beyond the repository level.

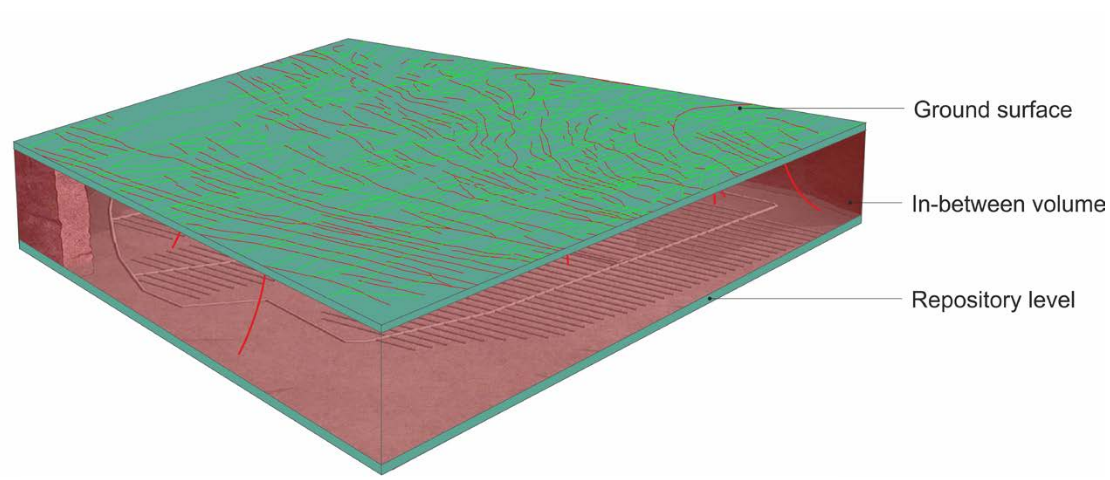


***Figure 5-8.** A schematic sketch showing the two levels of dense data distribution at the ground surface and the repository level (green), separated by a more sparsely informed, intermediate volume (red).*

5.4.4 Geometry – independent of scale

In the SDM-Site models, the resolution of deterministic structures is different in the local and regional model volumes. Each volume contains all modelled deformation zones down to a certain length, based on the measured lineament trace length on the ground surface. This means that the higher resolution local model includes all the zones of the SDM-Site regional model that intersect this volume. Thus, the geometric representation of the regional zones is identical in both the SDM-Site local and regional model volumes.

The concept of scale independent object detail is similar for visualization of structures in even smaller model volumes, which for instance may cover individual deposition areas or parts of deposition areas. The principle is that deterministic objects are modelled by <u>one</u> geometry regardless of the size of the model volume (or view window).

In the object library, the selection of objects to include in a model can be made on various properties, including size of geometry. For example, only large zones can be selected if this is the purpose of the model. If a higher degree of detail is needed, smaller objects can be included. But it is important to understand that each object geometry is always the same, regardless of the size of the model or viewing window as illustrated in Figure 5-9.

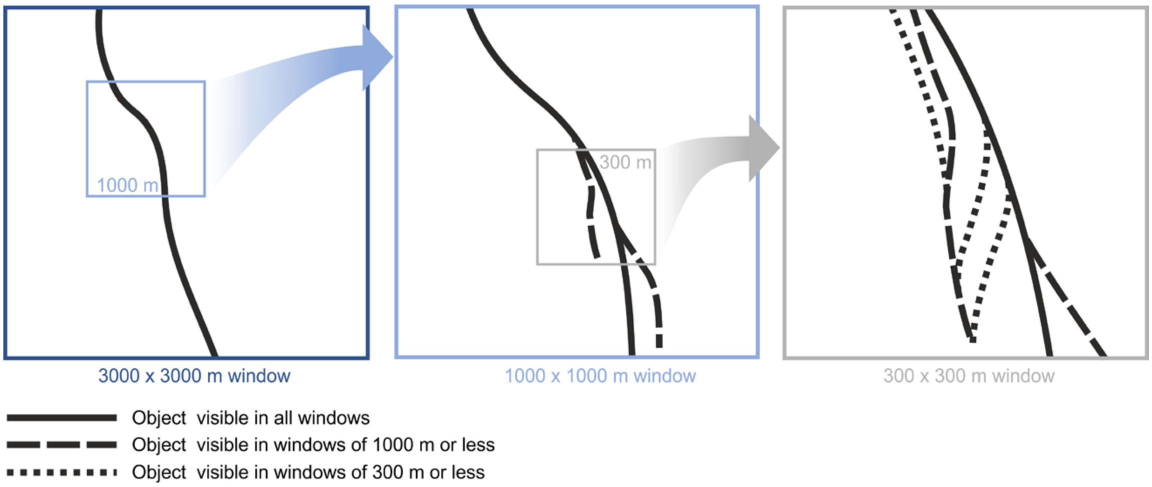


Figure 5-9. *Schematic sketch of the principle with visualization of all objects down to a certain size in a specific window.*

5.4.5 Geometric detail of modelled deformation zones

As part of the introduced methodology, modelled objects are given further deterministic detailed characteristics/properties according to the following guidelines:

- Zones and other structures are modelled with variable thickness, see further explanation below.
- Zone splays are modelled as separate objects (where data allows confident discrimination), Figure 5-10.
- The internal details of a zone/structure (e.g. fault core and damage zone) are described in borehole and tunnel intercepts but not modelled deterministically. This is because of the inability to interpolate structural details and variability over the distance of two adjacent deposition tunnels (or boreholes). Internal detailing of structures is suggested to be handled descriptively and/or through stochastic modelling, for example as by Hartley et al. (2018).
- To simplify the construction of the triangulated mesh geometry, as few fix points as possible should be used for each borehole or tunnel intercept. The locations of the fix points are determined during the GSHI and STI procedures, with possible adjustments during the modelling work.

Geometries and properties for deterministic zones in the existing SDM-Site models can be adjusted as observations in new boreholes and tunnels are obtained (Figure 5-10). New versions are created for every update. Older versions can be accessed in the object library if necessary, for re-modelling purposes, as exemplified in Figure 5-11. This figure illustrates a hypothetical example of a zone (1), which initially was identified in boreholes (A) and subsequently revised based on tunnel intercepts (B). Several splays to the zone are revealed by changing the view to a smaller volume/window (C). Note that all splays are modelled as separate objects.

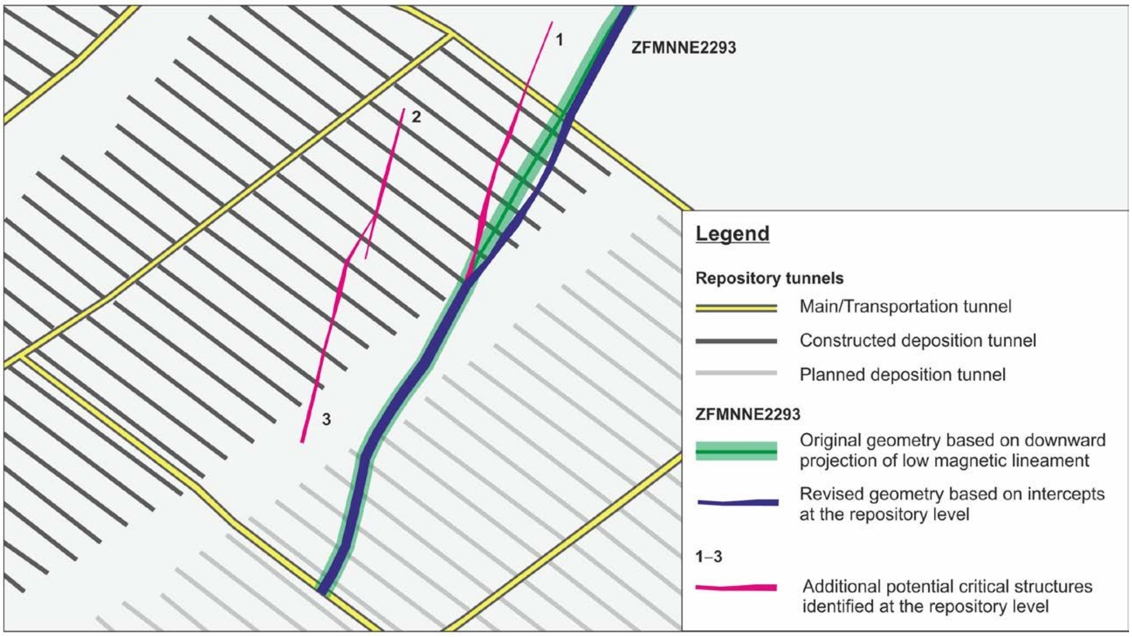


Figure 5-10. *Part of the repository area showing three deterministic deformation zones. ZFMNNE2293: Originally based on downward projection of a low magnetic lineament this zone has been subjected to a geometrical adjustment based on tunnel intercepts; the name and overall geometry is still the same. 1: A splay to ZFMNNE2293, which has been modelled as a separate zone based on tunnel intercepts. 2 and 3: Two separate parts of a zone identified during the excavation of a deposition area. All zones are modelled with variable thickness.*

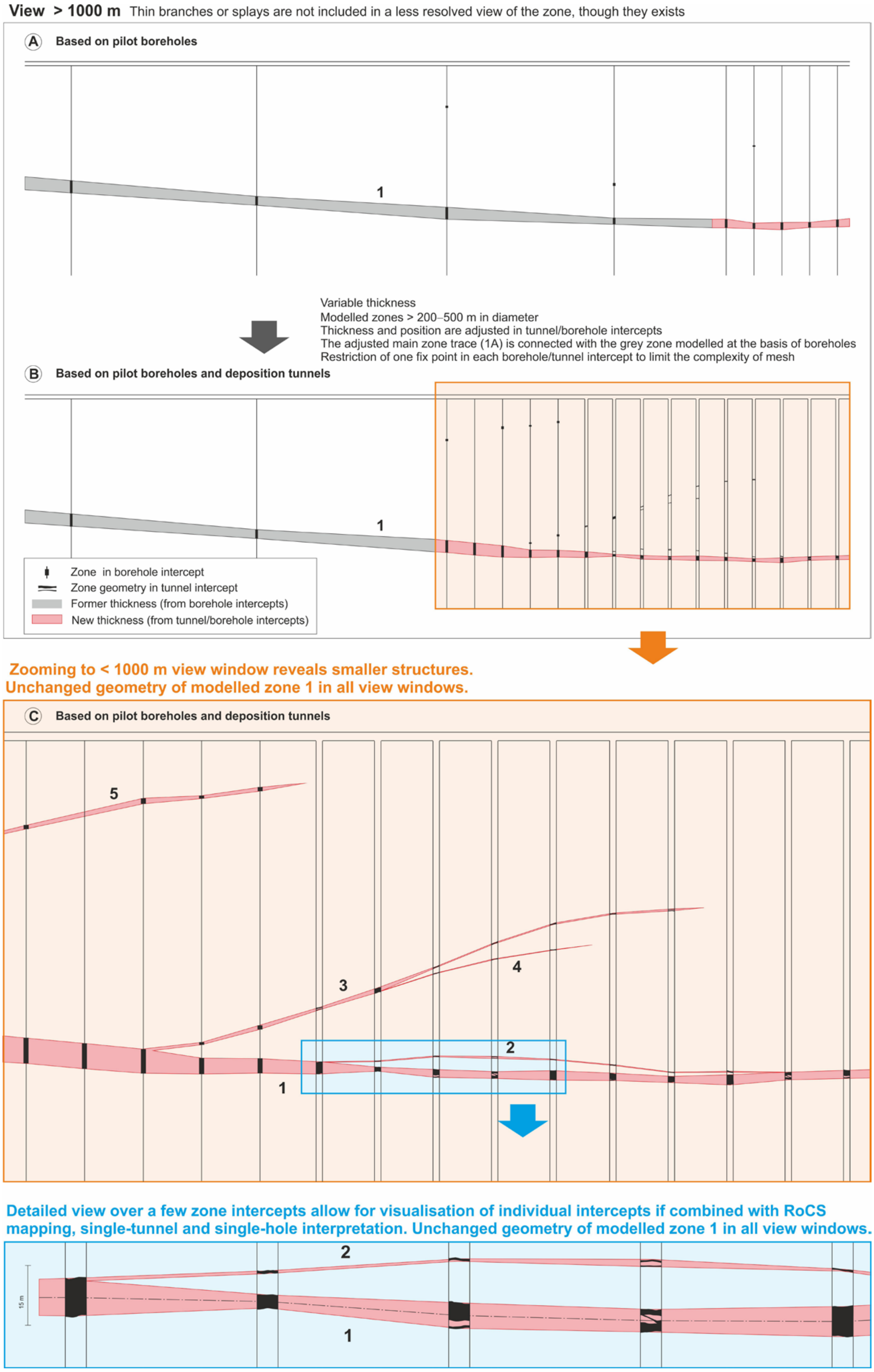


***Figure 5-11.** Details of the principle of scale-independent zone geometry.*

Deformation zones are modelled with variable thickness, if allowed by data. Traditionally, when zone thickness is illustrated it may have different meanings to different disciplines. Geologists may want to describe the whole deformation zone, including wall-rock alteration or increased frequency of sealed fractures linked to the zone formation or reactivation. Hydrogeologists and engineers may only consider the flowing, or weak parts of the zone which typically only involves a small portion of the geological thickness. These different interpretations are all valid for their intended purpose.

In this methodology, it is proposed that the modelled geological thickness in each observed intercept should reflect what the geologists consider being the *total zone thickness* (including both core and damage zone) according to the nomenclature used in Figure 1-4. Criteria to define the total zone thickness at each intercept are described in the GSHI and STI evaluations (see Appendices 2 and 3, as well as illustrated in Figure 2-2) and involve using the following primary and supporting indicators:

Primary indicators:
- Increased fracture frequency.
- Geometrical fracture arrangement.
- Fault rocks (breccia, mylonite, etc).
- Shear striae (grooves, slickensides, etc).
- Displacement of tectonic markers.

Supporting indicators:
- Hydrothermal alteration.
- Anomalous fracture widths (or apertures).
- Specific fracture filling.
- Caliper anomalies.
- Water inflows, mainly from hydraulic flow logging.
- Decreased resistivity.

In addition to variable thickness, it is suggested that the geometry describing zones is also represented by an average geometric mean surface that best fits the interpreted intercepts and extents (planar or curved), as supportive information to downstream applications.

Furthermore, it is required that the interpretation and character of the modelled thickness are explained in the description of the deformation zone (see Appendix 4). Thus, each individual deformation zone object is modelled and stored in the object description database (Figure 5-3) with its most conservative geometric form (central surface) and its interpreted variable thickness (volume).

5.4.6 Subsurface interpolation

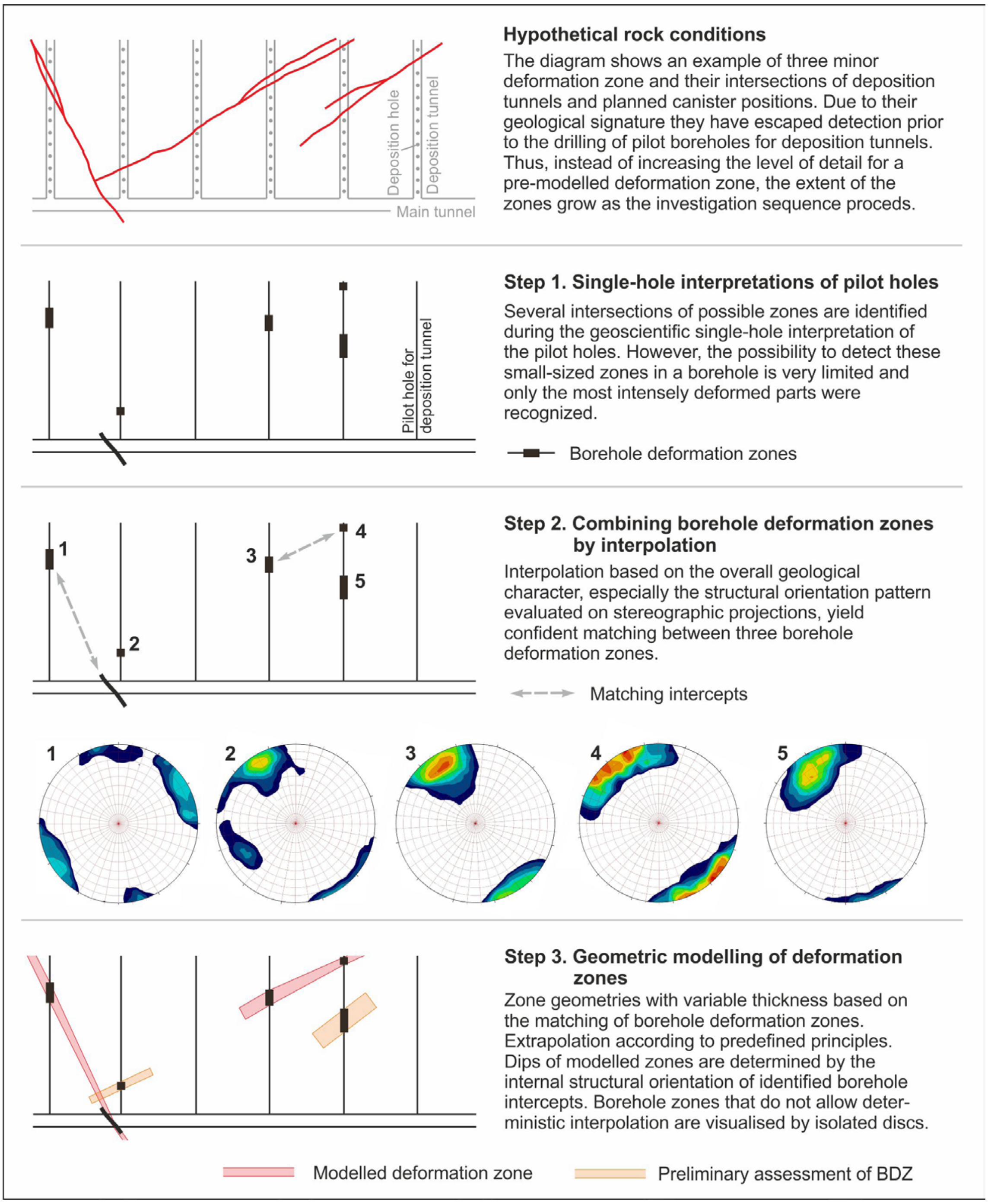
Lineaments, magnetic lineaments in particular, along with seismic reflectors integrated with borehole data, have provided the solid basis for the surface-based site descriptive modelling of deformation zones (Stephens et al. 2007). The importance of lineaments and seismic reflectors will remain, also when the input from subsurface data increases, especially for the continuous re-modelling of the large-scale structural framework. However, for minor structures that are encountered at depth during the construction, there will be no corresponding surface lineaments to provide information on extents and orientations. Instead, the basic principle for subsurface modelling of such structures will be interpolation between points of direct geological observations in boreholes and tunnels. This is done by using the single-hole and single-tunnel interpretations, with further support from indirect observations in available geophysical and hydrogeological data. Additional components in the interpolation work are the understanding of the geological processes of the site and conceptual models as illustrated in Figure 5-1. The procedure of subsurface interpolation is detailed below with a schematic summary in Figure 5-12.

All deterministic structures are modelled as two triangulated mesh surfaces defining its outer boundaries based on the orthogonal (to the strike direction) total zone thickness at each inferred borehole, tunnel and/or outcrop intercept. Thus, the thickness of the modelled structure is variable along its extent. The total thickness at each intercept is defined by the single-tunnel interpretation (i.e. the tunnel deformation zone, TDZ) and, where no tunnel data are available, by the borehole interpretation (i.e. the borehole deformation zone, BDZ).

The interpreted orientation of deterministically modelled structures is highly dependent on the distribution of the observation points along boreholes and tunnels. If the spatial distribution of these observation points is not enough to provide guidance, orientations can be derived from structural analysis of individual borehole and tunnel intercepts. The following interpolation principles apply:

- **Vertical to steeply dipping structures inferred to correspond to a lineament on the ground surface:** The strike of the modelled structure is assumed to be determined by the trend of the matching lineament. The decision to match a lineament with borehole/tunnel intercepts determines the dip of the modelled object.
- **Gently dipping structures identified based on seismic reflectors:** The orientation is provided by the inferred orientation of the reflector with adjustments for integrated borehole/tunnel intercepts.
- **Modelled structures that have three or more observation points (along boreholes, tunnels and/or outcrops) with a strongly nonlinear spatial arrangement:** The orientation is provided by the spatial distribution of the observation points.
- **Modelled structures that have two or more observation points (along boreholes, tunnels and/or outcrops) aligned in a linear arrangement along its strike:** The strike of the modelled object is assumed to be determined by the trend of the observation points, whereas the dip is based on the general structural distribution pattern within each borehole/tunnel intercept, evaluated from stereographic projections.
- **Modelled structures that have only two observation points (along boreholes, tunnels and/or outcrops) with a non-horizontal spatial arrangement:** The strike of the modelled structure is based on the orientation of the zone core or the inferred zone boundaries along with additional support from the general fracture orientation pattern within each borehole/tunnel intercept, evaluated on stereographic projections. The dip is determined by the relative position of the two observation points.
- **Structures that are only observed in one borehole or tunnel (through GSHI or STI) are not modelled in 3D.**

The deterministic modelling is largely a geometrical exercise supported by conceptual assumptions, where the spatial location of subsurface observation points steers whether interpolation is possible. In addition, interpolation must make use of the overall geological character of the structure, in particular the analysis of the orientation pattern of brittle and brittle-ductile structures along the inferred borehole/tunnel intercepts with respect to the current geological knowledge. In addition to mapped fractures, this means that the analysis must be expanded to involve other less frequent structural features such as breccias, cataclasites, shear zones and fractures within sealed networks and crushes registered along boreholes and different fracture sets recorded in areas of intense deformation along a tunnel. Other geological descriptors to support an interpolation are fracture filling minerals, wall-rock alterations, deformation intensities and evaluation of kinematic indicators. The procedure to interpolate between several observations can utilize temporary 3D geometries (often discs) as preliminary assessments of individual BDZ and TDZ orientations and thicknesses, cf Figure 5-12.



Hypothetical rock conditions

The diagram shows an example of three minor deformation zone and their intersections of deposition tunnels and planned canister positions. Due to their geological signature they have escaped detection prior to the drilling of pilot boreholes for deposition tunnels. Thus, instead of increasing the level of detail for a pre-modelled deformation zone, the extent of the zones grow as the investigation sequence proceds.

Step 1. Single-hole interpretations of pilot holes

Several intersections of possible zones are identified during the geoscientific single-hole interpretation of the pilot holes. However, the possibility to detect these small-sized zones in a borehole is very limited and only the most intensely deformed parts were recognized.

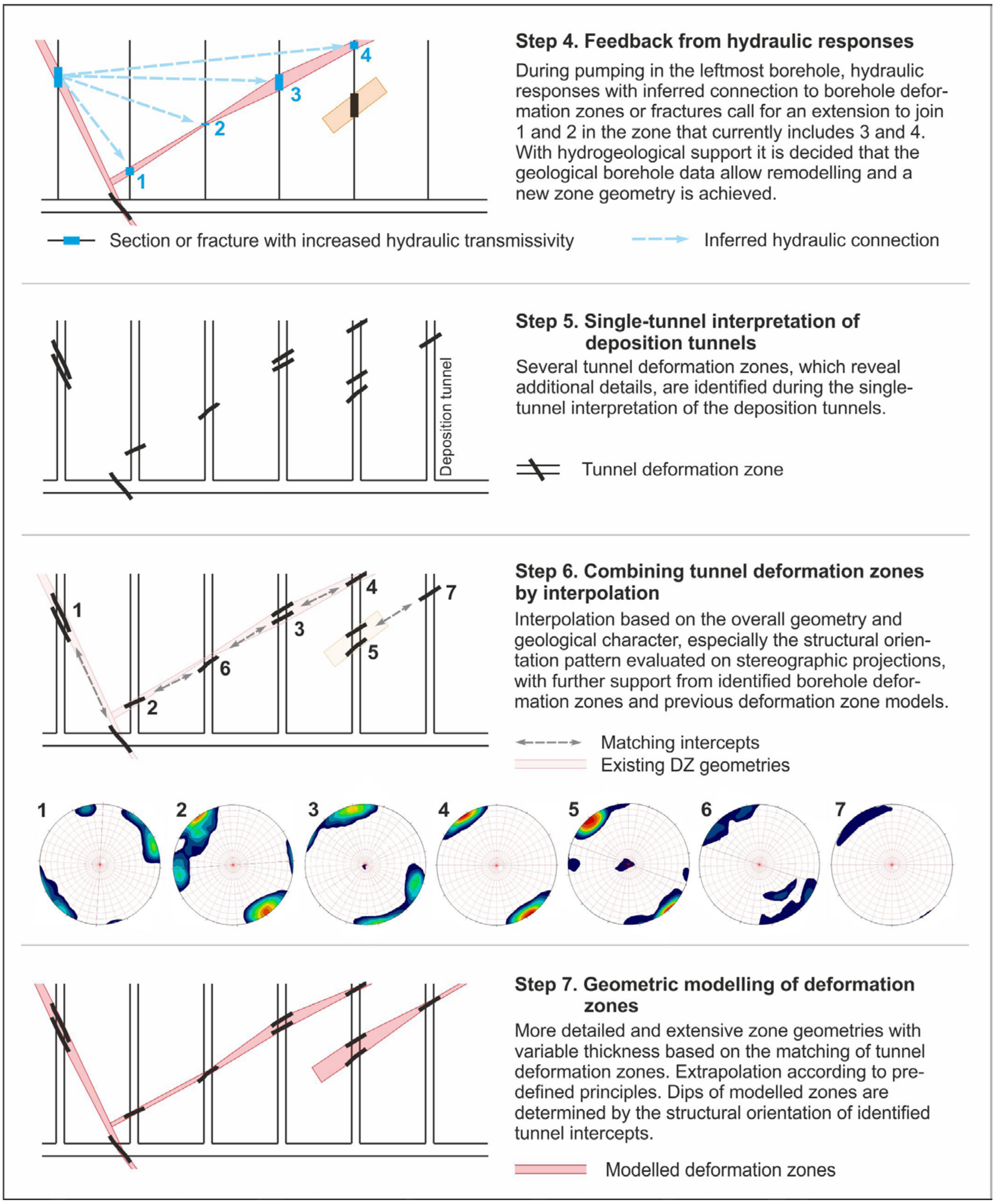
Step 2. Combining borehole deformation zones by interpolation

Interpolation based on the overall geological character, especially the structural orientation pattern evaluated on stereographic projections, yield confident matching between three borehole deformation zones.

Step 3. Geometric modelling of deformation zones

Zone geometries with variable thickness based on the matching of borehole deformation zones. Extrapolation according to predefined principles. Dips of modelled zones are determined by the internal structural orientation of identified borehole intercepts. Borehole zones that do not allow deterministic interpolation are visualised by isolated discs.

Figure 5-12a. *Highly schematic sketch showing an example of a possible interpretation-modelling sequence for potential critical structures during the investigation and excavation of deposition tunnels, with the following steps: (1) identifying intercepts for borehole deformation zones in individual pilot boreholes, (2) combining borehole deformation zones by interpolation, and (3) geometrical modelling of deformation zones based on borehole interpretations.*



Step 4. Feedback from hydraulic responses

During pumping in the leftmost borehole, hydraulic responses with inferred connection to borehole deformation zones or fractures call for an extension to join 1 and 2 in the zone that currently includes 3 and 4. With hydrogeological support it is decided that the geological borehole data allow remodelling and a new zone geometry is achieved.

Step 5. Single-tunnel interpretation of deposition tunnels

Several tunnel deformation zones, which reveal additional details, are identified during the single-tunnel interpretation of the deposition tunnels.

Step 6. Combining tunnel deformation zones by interpolation

Interpolation based on the overall geometry and geological character, especially the structural orientation pattern evaluated on stereographic projections, with further support from identified borehole deformation zones and previous deformation zone models.

Step 7. Geometric modelling of deformation zones

More detailed and extensive zone geometries with variable thickness based on the matching of tunnel deformation zones. Extrapolation according to predefined principles. Dips of modelled zones are determined by the structural orientation of identified tunnel intercepts.

Figure 5-12b. *Highly schematic sketch showing an example of a possible interpretation-modelling sequence for potential critical structures during the investigation and excavation of deposition tunnels, with the following steps: (4) feedback from hydraulic interference tests with possible re-modelling, (5) identifying tunnel deformation zones in deposition tunnels, (6) combining tunnel deformation zones by interpolation, and (7) geometrical modelling of deformation zones, often thinner and with more details than the previous geometries obtained from borehole data.*

Compilations of key geological parameters for interpolation are presented in Table 5-1. Preferably the matching is based on the overall structural character, focusing on deformation style and structural orientation as indicative features. The lodestar in this process should be the conceptual understanding of the various structures, which is expected to evolve throughout the constructions at the site.

With weak or even a lack of discriminating geological information, responses of hydraulic interference tests and possibly low-velocity anomalies in the seismic reflection data might be used as guidelines to link individual sections in different boreholes. However, the confidence of these interpretations tends to be low. The significance and practicality of such measures need to be tested and verified at repository depth prior to decision of implementation. Hydraulic responses have a more decisive role for the modelling of stress release structures near the surface, but should always be used in close association with the geoscientific single-hole interpretation. It is emphasized again that the inferred hydraulic connection or geophysical anomalies between different boreholes only provides indirect support to geological observations. Thus, based on underlying geological concepts, hydraulic responses or geophysical anomalies can add confidence to the interpretation and support alternative interpretations.

Table 5-1. Key geological parameters for correlation between intercepts of deformation zones in boreholes, tunnels and outcrops. The matching of two closely situated intercepts needs to make use of the overall character of the deformational structure, which covers all listed key parameters.

Parameter
Spatial location of intercepts
Deformation style (brittle, brittle-ductile or ductile)
Deformation intensity: *Fracture frequency* *Crushes and fault rocks (cataclasite, breccia, mylonite, etc)* *Relative proportion of damage zone and fault core* *Sense of displacement*
Orientation pattern of structural data evaluated on stereographic projections: *Borehole data (open and sealed fractures, crushes, sealed networks and fault rocks)* *Tunnel and outcrop data (fractures and deformation zones, including fracture sets)*
Thickness (true thickness of intercept)
Rock alteration – type and intensity
Mineral filling
Inflow of water (transmissivity in boreholes)

The use of structural orientation patterns associated with borehole/tunnel deformation zones as a guideline for interpolation requires identification and parameterization of fracture clusters. Several numerical methods are available for this task, as detailed by Munier (2004) and references therein. The recommended method, previously used during the site descriptive modelling for Forsmark (Stephens et al. 2007), includes identification of clusters by visual inspection with a subsequent orientation parameterization of fracture set mean poles and their dispersion around the mean. A manual sectoring based on visual inspection is preferred, as it allows the application of geological experience and due consideration of local geological conditions.

5.4.7 Subsurface extrapolation

When extrapolating deterministic structures beyond their observation points, consistency in the method used is important as well as to constrain the extrapolation to a distance within which the geologist can have reasonable confidence in the validity of extrapolation. Therefore, structures will be deterministically modelled up to their assumed minimum geometric extent. Stochastic simulation is an option to capture and superimpose the added uncertainty related to their maximum extent, as described further in Chapter 6.4.

The primary basis for extrapolation must always be the underlying conceptual geological understanding of the site but needs also to include geometrical guidelines when other options are exhausted. Based on this, the subsurface extrapolation of structures is carried out using the following procedure, as illustrated in Figure 5-13 and Figure 5-14:

1. The extent of deformation zones is constrained by the pattern of high confidence zones, or by strong geometrical control from surrounding tunnels and boreholes. If there is clear evidence that a structure does not intersect a tunnel or borehole, a reasonable practice is to limit the extrapolation of the structure halfway from the last known point, as illustrated in Figure 5-14.
2. Expert judgement, for example by comparison with other modelled high confidence zones with similar geological and geometrical characteristics and orientations according to the accepted conceptual model, as illustrated in Figure 5-13.
3. Existence of fault rocks or indicators showing a slip of more than several decimetres to define a minimum zone size. A zone with such kinematic indicators will be classified as a potentially critical structure (cf Cosgrove et al. 2006).
4. In the extreme case that the three principles above do not provide any information for extrapolation, the structure can be extended beyond the outermost observation point up to 1/3 of the maximum distance between observed tunnel or borehole intercepts, as long as it does not intersect another object (structure or tunnel/borehole), as illustrated in Figure 5-14. Where there is geometric control (i.e. lack of intercept with a tunnel or borehole), the extrapolation shall be constrained to half the distance to the nearest point of observation. The restriction to extrapolate beyond the 1/3 distance is based on maintaining a reasonable confidence in the interpretation across the whole structure. However, this measure should be continuously reassessed as experience from the excavations increase. This last approach should be used with care, especially for structures close to the size threshold of becoming potentially critical as it can have profound implications of underestimating the size of a structure.

The combination of these principles ensures that extrapolation is executed in a consistent manner where the confidence in the interpretation can be objectively assessed (cf Section 6.1.4). However, as principle 4, and to some extent 2, may lead to underestimating size, it may be necessary to make an individual assessment if the structure could be larger than a critical radii > 200 m. The assessment should be noted in the zone description such that possible larger extents can be stochastically addressed using DFN modelling (see Section 6.4).

According to studies carried out by Cowie and Scholz (1992a, b) , fault displacements larger than 0.5–1 m suggests that unbounded faults are likely to be larger than 200 m in radii. As a precautionary principle, it is suggested that a displacement of several decimetres provides grounds for extrapolation of such structures to > 400 m horizontal length.

Variable thickness is achieved by interpolating between intersection points as described in Section 5.4.5. When extrapolating the deformation zone beyond the observation, thickness should first be based on the available conceptual understanding. In case such concepts have not been developed, it is considered neutral to use the average observed thickness.

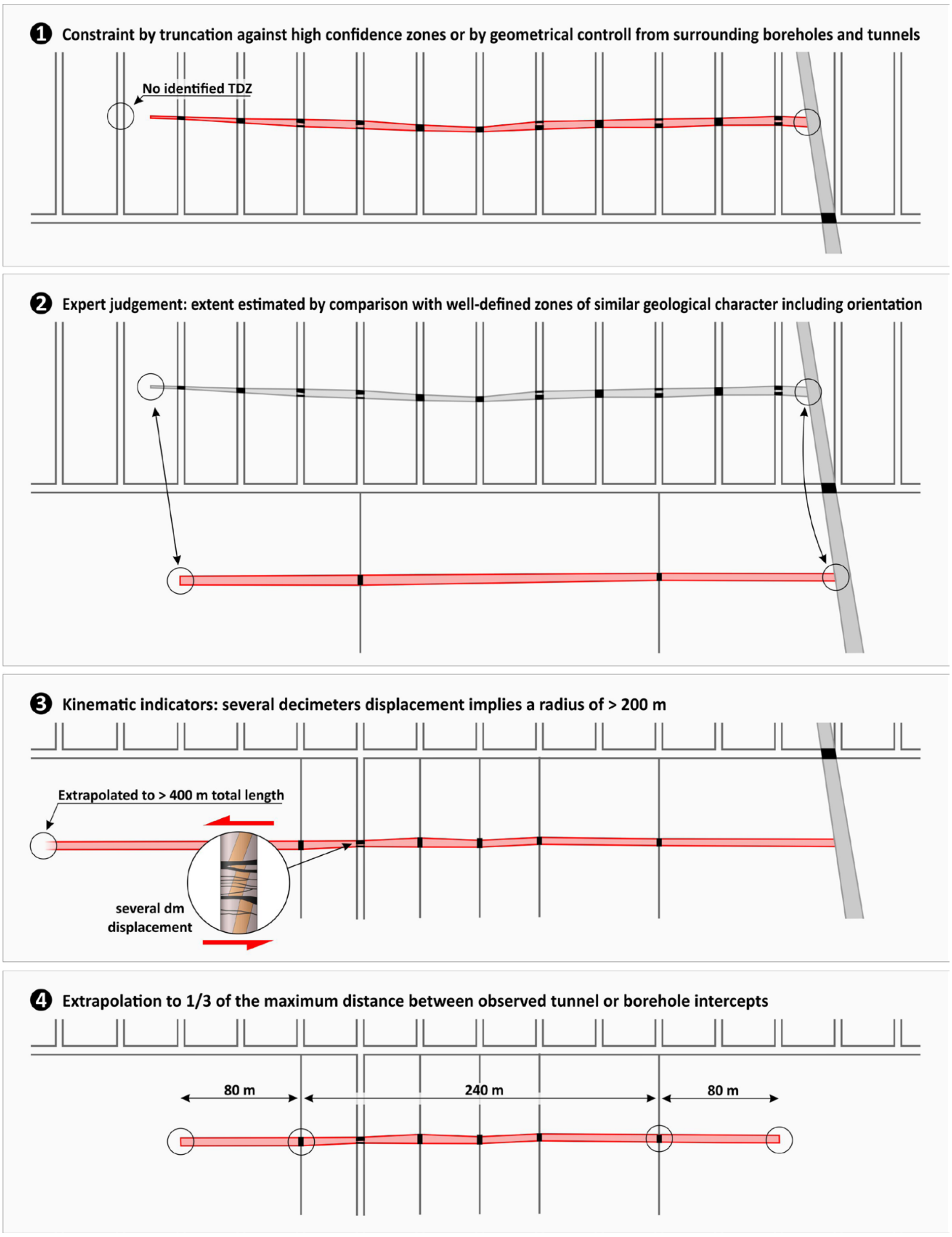


Figure 5-13. *Sketch illustrating the procedure for subsurface extrapolation of deformation zones. The choice of extrapolation method is depending on observed constraints, the structural context, and the presence of modelled structures with similar orientation.*

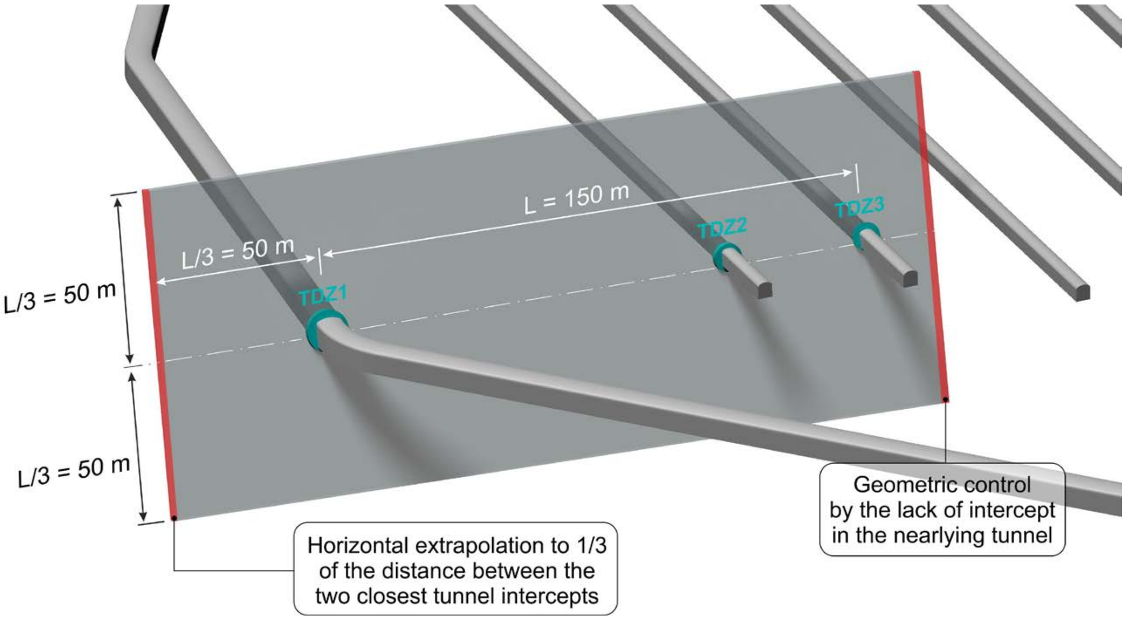


Figure 5-14. *Illustration of a tentative deformation zone in the repository area modelled based on observation points (TDZ) along three tunnels. Extrapolation along the strike and dip directions are done by: (1) existing control beyond TDZ3 by the lack of geological indications in the next deposition tunnel, and (2) in the extreme case that the three principles above do not provide any information for extrapolation, the structure can be extended beyond the outermost observation point up to 1/3 of the maximum distance between observed tunnel or borehole intercepts, as long as it is not intersecting another object (structure or tunnel/borehole).*

5.4.8 Assessment of individual near-surface sheet joints

The fact that these features are joints, developed by tensional failure sub-parallel to the ground surface interface in the shallow rock mass, calls for alternative approaches for identification and modelling. The lack of shear component means that there exists no support from kinematic indicators for interpolation. Moreover, their dilatational nature has significant implications for the possibility of extrapolation and the mode of termination.

Sheet joints occur abundantly in the near-surface of the Forsmark area. The challenge is to identify individual joints of an extent that allows deterministic modelling which may have importance as potential flow paths. Information from the construction of the nuclear power plants in Forsmark (Carlsson 1979), suggests that for sheet joints with a lateral size of several tens of meters or more aperture is the only reliable proxy. With this in mind, sheet joints in Forsmark that are large enough be deterministically modelled the following criteria has been used for fractures and crushes in boreholes:

- Dip of ≤ 30°, but typically < 10°.
- No discernible slip.
- No discernible mineral coating or wall-rock alteration.
- Distinct aperture, i.e. ≥ 1 mm.

Examples of typical sheet joints that fulfils these criteria are presented in Figure 5-15.

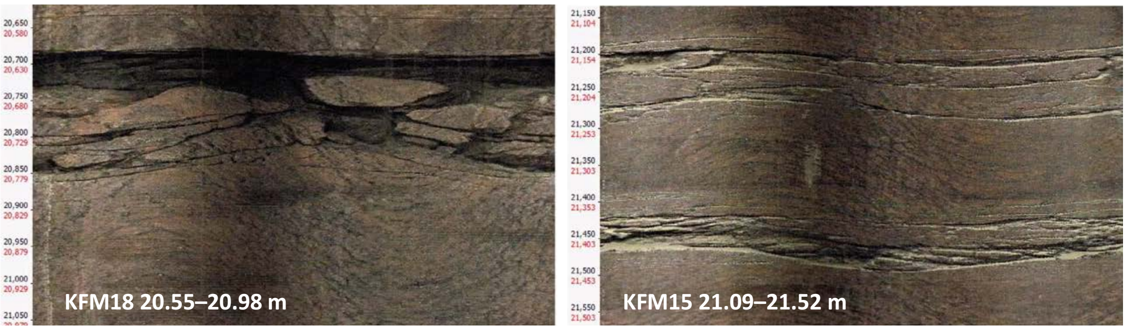


***Figure 5-15.** OPTV-images showing examples of sheet joints with distinct aperture in two boreholes (KFM15 and KFM18) drilled in Forsmark.*

Deterministic modelling of the identified sheet joints is based on two fundamental assumptions concerning orientation and extent:

- In Forsmark, sheet joints close to the surface tend to be sub-parallel to the bedrock surface. Due to the relatively flat bedrock surface, all sheet joints at depth > 10 m are inferred to be horizontal to sub-horizontal (dips ≤ 2°).
- The largest individual sheet joints can reach lateral dimensions up to a few hundred meters.

In accordance with these assumptions, the following approach is recommended:

- A deterministically modelled sheet joint must be based on three or more observation points.
- Interpolation based on geological observations is limited to a maximum horizontal distance of 100 m (the approximate radius of the longest joint trace along the inlet channel (cf Carlsson 1979). Additional extrapolation up to a few tens of meters is possible with support from hydraulic responses.
- To allow interpolation, observation points must be located at approximately the same elevation, ± 1 m.
- Interpolation between observation points is not necessarily dependent on hydraulic connectivity, due to the local occurrence of sediment filling (see Figure 5-16).
- If data permits, surfaces can be modelled by variable thickness.

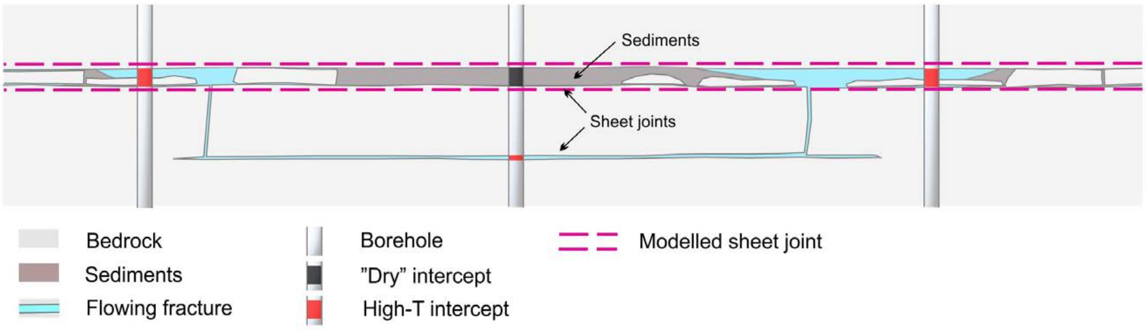


***Figure 5-16.** Schematic sketch of the principles for deterministic modelling of individual sheet joints by combination of both "dry" and high-transmissivity fractures/crushes located at approximately the same level.*

Termination of sheet joints is a modelling issue that requires special attention. Based on their dilatational nature, sheet joints are expected to cross both older, steeply dipping geological structures as well as lithological boundaries. They may also interact with gently dipping deformation zones, and terminations can occur due to a competence difference within the rock mass. However, the vast majority fade out without any obvious structural or lithological explanation. This will lead to implications for confident extrapolation as it differs slightly to the methodology used for shear-induced deformation zones. For modelling purposes, a sheet joint is extrapolated beyond each peripheral observation point to a horizontal distance that corresponds to 1/3 of the maximum distance between nearby observations according to the following procedure, as illustrated in Figure 5-17:

- The maximum distance between nearby observation points is defined.
- Insert horizontal discs with a radius that corresponds to 1/3 of the defined maximum distance.
- The outer discs then define the limit of the modelled surface. Surface edges are drawn straight between these discs using as simple geometry as possible.
- All observation points are used as fix points to specify the surface undulation.
- The surface edges are adjusted to avoid intersections with boreholes (and tunnels) that lack observations.

Hydraulic responses have been used to extend the distance of interpolation to more than 100 m. This requires that *both* the pumped and responding borehole sections include high-transmissivity observations that are correlated with identified sheet joints located at approximately the same elevation. The maximum recommended distance of interpolation based on supporting hydraulic information is 120–130 m, which corresponds to approximately 1.5 times the observed radius of sheet joints in the area (Carlsson 1979). However, sheet joints modelled on this assumption are assigned a lower confidence level, primarily due to an increased interpolation distance between the observation points (cf Chapter 6).

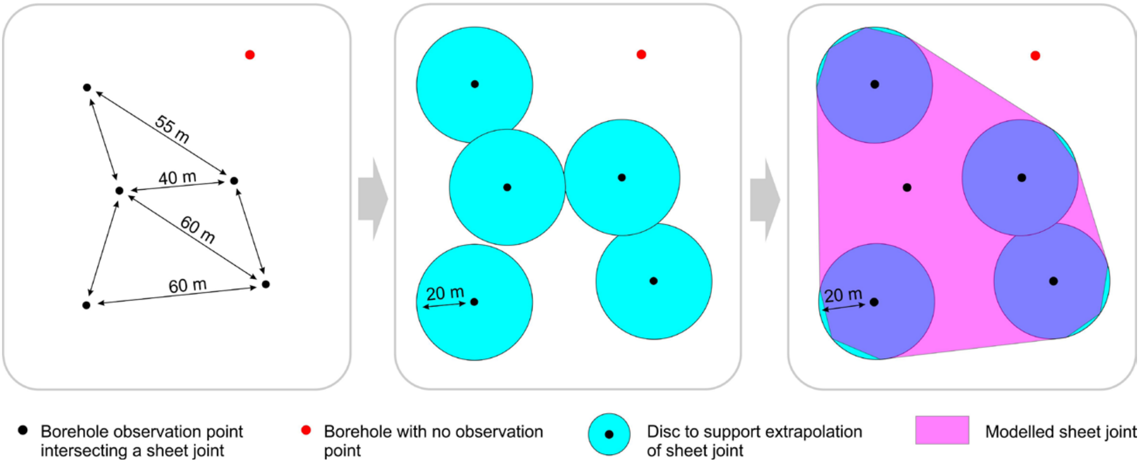


Figure 5-17. *The illustration exemplifies the process of extrapolation from intersections of a sheet joint by five vertical boreholes.*

5.5 Process for modelling domains and other volumes

The use of domains can greatly aid in describing the geology of the site, by introducing appropriate parameterisation. Rock volumes regarded as similar with respect to a particular property can be grouped together in domains, thus decreasing the number of objects to be manually handled in the model. The starting point for the domain modelling is the rock units defined during the ground surface bedrock mapping, as well as the GSHI and STI. Two types of geological domains were introduced during the preceding site descriptive modelling: fracture domains and rock domains. These two types of domains are expected to cover the future needs also during the construction and operational phases of the future repositories and are consequently the focus of the proposed methodology presented in this section. The methodology for creating domains is identical to that described by Munier et al. (2003) with the basic geometrical guidelines presented in the nomenclature Section (1.5).

The methodology to extrapolate rock domains in 3D space builds on evaluating how the groups of rock types visible in the bedrock geological map can be volumetrically defined using conceptual tectonic understanding together with observations of mineral fabric and degree of deformation. During the preceding site investigations, the 3D domains were largely defined by the bedrock geological map, observations on the surface together with support from a few needle sticks in boreholes and indirect support by airborne geophysics (magnetics and gravity). This information was then evaluated in light of the large scale geological and tectonic developments in south–eastern Sweden. This resulted in a model where the contacts between the rock domains are predominantly steeply dipping and, by correlation with interpreted rock domains along cored boreholes, most of them are assumed to extend downwards to, at least, the base of the SDM-Site regional model volume (i.e. −2 100 m depth).

As a prerequisite for DFN modelling, the rock domains (minus the volume occupied by deterministic deformation zones) have been further divided into fracture domains at Forsmark (Olofsson et al. 2007). With the assumption that the rock domain characteristics exert control on the fracture frequency distribution pattern, a majority of the fracture domain boundaries correspond to those of individual or combined rock domains. In addition, there is a marked contrast in the fracture frequency distribution pattern with depth, which by support from a multidisciplinary assessment, of especially geological, hydrogeological and hydrogeochemical data, has motivated further sub-division into shallow fracture domains (i.e. FFM02 and FFM03). The comprehensive analysis and evaluation of properties to define fracture domains will be carried out as part of the stochastic DFN modelling methodology (Selroos et al. 2022).

The domain modelling will be executed in the same manner during the future stages of underground constructions where it is expected that the more detailed information from boreholes and tunnels will allow for further evaluation of the geological and tectonic concept as well as adjustments and refinements to both rock and fracture domain geometries. The proposed guidelines for this work follow, as far as possible, the assumptions applied during the preceding surface-based site descriptive modelling at Forsmark, which are listed in Section 2.1.2 (cf Stephens et al. 2007).

A further sub-division of large-scale rock domains appears to be necessary only in proximity to the deep repository, both as input to thermal modelling and to support layout decisions (e.g. rejection of canister positions). However, modelling of small-scale domains can lead to complicated geometrical and topological issues in the 3D modelling if all domain boundaries are spatially connected (space-filling geometry). It is therefore proposed to be restrictive in introducing small 3D domain geometries with spatially connected domain boundaries into the model. To define domains of potentially critical volumes at the repository level, small-scale domain geometries without connected domain boundaries can be used (i.e. floating inside other larger connected domains), see example in Figure 5-18.

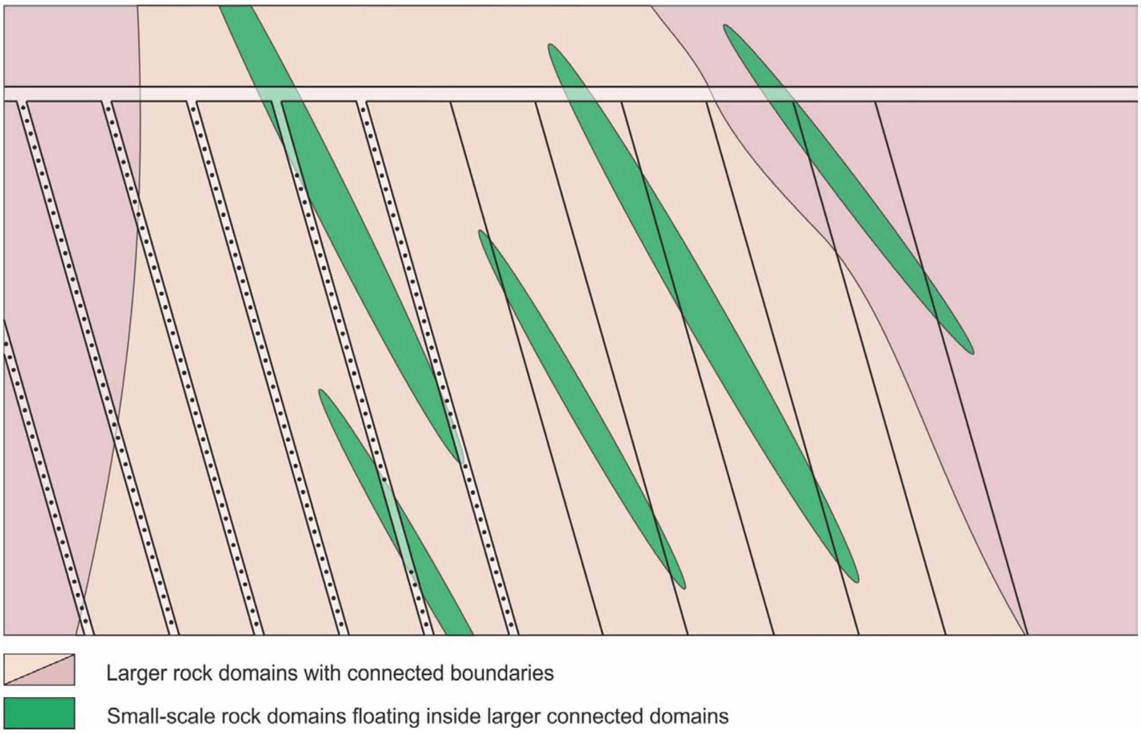


Figure 5-18. *Schematic 2D sketch of a partly excavated deposition area exemplifying the use of subordinate rock domains (green ellipses representing generalised bodies of amphibolite) floating inside larger, spatially connected domain boundaries (brown shades).*

An issue of significance for the identification of potentially critical volumes is the minimum size or extent that a geological object with unfavourable properties must attain before it can be regarded as critical. For example, a rock unit distinguished in the GSHI or STI procedure should be as large as possible with respect to thermal modelling requirements. Thus, the size of the smallest defined rock unit depends on the scale at which variations of thermal conductivity is significant for the maximum temperature of the canister. Lönnqvist[6] has shown that a buffer temperature is to some extent affected by 1–2 m low-conductivity rock around a deposition hole. However, canisters only partly surrounded by low-conductivity rock types have not yet been considered in her analyses. For rock types with anomalously low thermal conductivity (such as the amphibolite), it is concluded that the minimum size of a critical rock unit is in the order of 1–2 m.

The approach presented for deterministic modelling of subordinate domains with tabular shapes or with elongations in the direction of the mineral stretching lineation is largely similar to the methodology prescribed for critical structures. Simplistic ellipsoids or flattened rod-shapes can be used to model these volumes. Within the deposition areas, identified bodies of subordinate rocks and alterations that are inferred to reach potentially critical volumes are modelled deterministically according to the following guidelines (see Figure 5-19):

- Interpolation between points of direct geological observation in boreholes and tunnels.
- Individual bodies or volumes are represented by disc-like ellipsoids.

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[6] Lönnqvist M, 2018. Potential for optimization of the repository layout at the Forsmark site: influence of low-conductivity rock volumes. SKBdoc 1700389 ver 1.0, Svensk Kärnbränslehantering AB. (Internal document.)

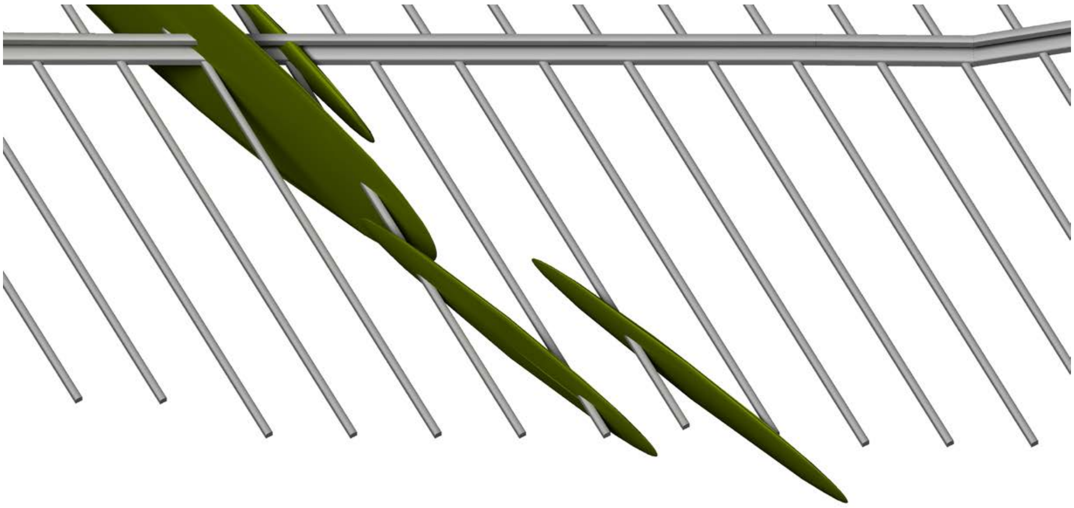


Figure 5-19. *Deterministic modelling of subordinate domains exemplified by a hypothetical amphibolite swarm. Individual occurrences, ranging up to tens of meters in thickness, are represented by disc-like ellipsoids that are floating inside more extensive domains (cf Figure 5-18).*

Subsurface deterministic modelling of subordinate rock and fracture domains is highly dependent on the underlying concept, which requires extensive understanding of the geological conditions of a site. The focus in the repository area is to identify volumes of the rock mass that exhibit anomalously thermal and/or hydraulic properties. For Forsmark, this includes the following geological features:

- Metamorphosed dykes and lenses of amphibolite with associated albitized rocks (potentially in rock domains RFM029 and RFM045).
- Vuggy, quartz-deficient, alteration rock referred to as episyenite, with an apparent association to brittle high-strain zones, which has mechanical weaknesses and hydraulic pathways that can be critical for the canister integrity.
- Belts of more intense ductile deformation, especially along the margins of the tectonic lens (i.e. rock domains RFM029 and RFM045).

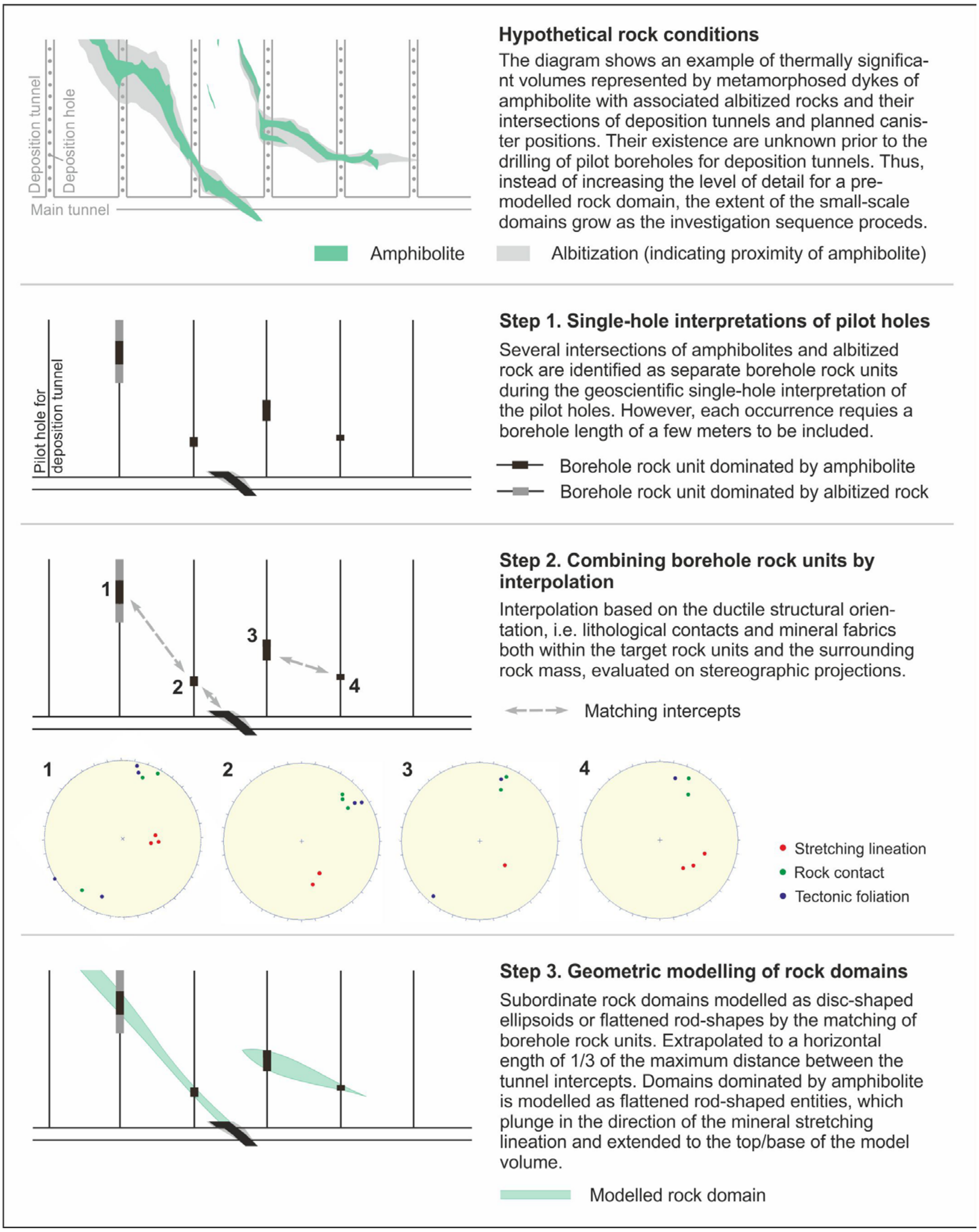
The geometries and spatial distribution of all these features are controlled by the deformation pattern in the area. For modelling of amphibolites of relevant size, the proposed approach follows the concept of Stephens et al. (2007), where all isolated bodies of metamorphosed intrusive rocks are treated as constrictional, rod-like structures that extend sub-parallel to the mineral stretching lineation.

Subsurface extrapolation of subordinate domains relies virtually on the same principles as proposed for deformation zones in Section 5.4.7:

1. Expert judgement by comparison to other closely situated domains with similar geological and geometrical characteristics and orientations.
2. If the first principle does not provide sufficient information for confident extrapolation, the domain can be extended beyond the outermost observation point up to 1/3 of the maximum distance between observed tunnel or borehole intercepts, as long as it is not intersecting another object (structure or tunnel/borehole), whilst maintaining their conceptual geometry.

Observations of potentially critical volumes in only one borehole or tunnel (through GSHI or STI) are generally not extrapolated in 3D.

A summary of the interpretation-modelling sequence concerning subordinate rock domains is illustrated by an example in Figure 5-20.



Hypothetical rock conditions

The diagram shows an example of thermally significant volumes represented by metamorphosed dykes of amphibolite with associated albitized rocks and their intersections of deposition tunnels and planned canister positions. Their existence are unknown prior to the drilling of pilot boreholes for deposition tunnels. Thus, instead of increasing the level of detail for a pre-modelled rock domain, the extent of the small-scale domains grow as the investigation sequence proceds.

Step 1. Single-hole interpretations of pilot holes

Several intersections of amphibolites and albitized rock are identified as separate borehole rock units during the geoscientific single-hole interpretation of the pilot holes. However, each occurrence requies a borehole length of a few meters to be included.

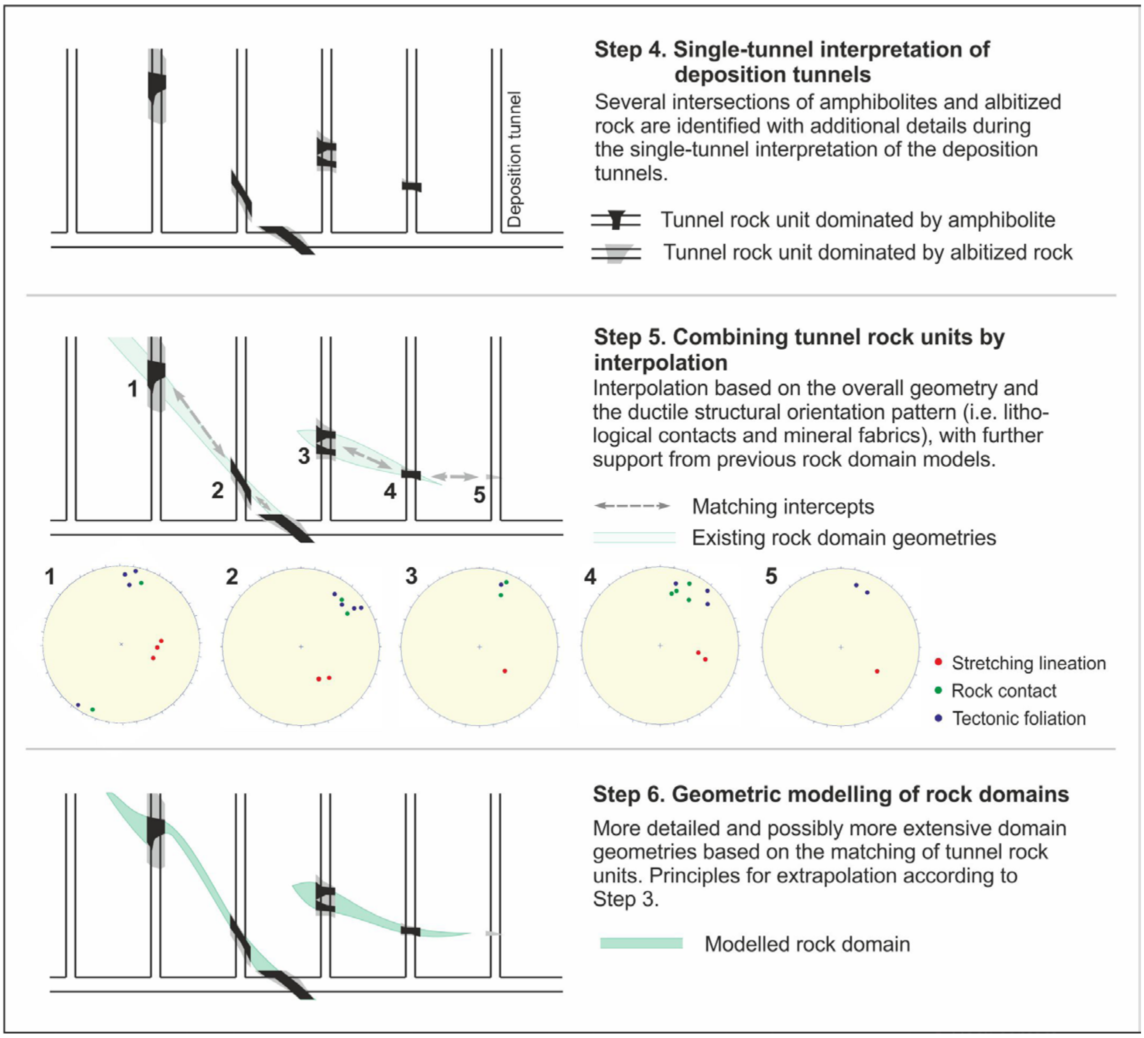
Step 2. Combining borehole rock units by interpolation

Interpolation based on the ductile structural orientation, i.e. lithological contacts and mineral fabrics both within the target rock units and the surrounding rock mass, evaluated on stereographic projections.

Step 3. Geometric modelling of rock domains

Subordinate rock domains modelled as disc-shaped ellipsoids or flattened rod-shapes by the matching of borehole rock units. Extrapolated to a horizontal ength of 1/3 of the maximum distance between the tunnel intercepts. Domains dominated by amphibolite is modelled as flattened rod-shaped entities, which plunge in the direction of the mineral stretching lineation and extended to the top/base of the model volume.

Figure 5-20a. *Schematic sketch showing an example of a possible interpretation-modelling sequence for subordinate rock domains during the investigation and excavation of deposition tunnels, with the following steps: (1) identifying intercepts for rock units in individual pilot boreholes, (2) combining rock units by interpolation, and (3) geometrical modelling of subordinate rock domains based on borehole interpretations.*



Step 4. Single-tunnel interpretation of deposition tunnels

Several intersections of amphibolites and albitized rock are identified with additional details during the single-tunnel interpretation of the deposition tunnels.

Step 5. Combining tunnel rock units by interpolation

Interpolation based on the overall geometry and the ductile structural orientation pattern (i.e. lithological contacts and mineral fabrics), with further support from previous rock domain models.

Step 6. Geometric modelling of rock domains

More detailed and possibly more extensive domain geometries based on the matching of tunnel rock units. Principles for extrapolation according to Step 3.

Figure 5-20b. *Schematic sketch showing an example of a possible interpretation-modelling sequence for subordinate rock domains during the investigation and excavation of deposition tunnels, with the following steps: (4) identifying rock units in deposition tunnels, (5) combining rock units by interpolation, and (6) geometrical modelling of subordinate rock domains.*

5.6 Geological identification of potentially critical structures and volumes based on size and unfavourable thermal properties

This section describes the process of identification and assessment of structures with a risk for shear exceeding the threshold distance of 5 cm and rock volumes with unfavourable thermal properties, cf Figure 2-5. The assessment of potentially critical structures only exhibiting significant flow paths, cf Figure 2-5, is not covered here as it cannot be assessed directly in the deterministic geological models and thus require further analysis through hydrogeological modelling. The final classification of critical structures/volumes should be determined in a formalised decision process involving all relevant parties at SKB and is not part of the geological modelling methodology. The geological assessment of potentially critical structures/volumes constitutes input to this process.

The geological assessment of potentially critical structures or volumes involves a distinction between class 2 and 3 (i.e. CS2/CV2 from CS3/CV3) based on their interpreted geological character. Individual parameters delivered by the geological mapping are rarely decisive in this process. Instead, the assessment rely on a number of geological, hydrogeological and geophysical indicators (proxies), which are evaluated collectively in light of the conceptual understanding. The primary basis of this process is geological judgement and the identification can therefore not be controlled by fixed values of individual indicators or parameters.

In cases where kinematic indicators show accumulated brittle movement of several dm or more the structure can potentially be of critical size > 200 m equivalent circular radius (Cowie and Scholz 1992a, b). However, accumulated movements need to be assessed considering the history of past stress conditions as well as the orientation, size, and mechanical properties of the structure in relation to present stress conditions. Similarly, the presence of large volumes of quartz-deficient rock types (e.g. amphibolite) can potentially be recognised as critical volumes due to the unfavourable thermal properties. The structures/volumes in the geological model will be identified by an assessment of several indicators, which collectively provide confidence to decisions on their potentially critical nature.

Characteristics judged to be of significance for the identification of borehole/tunnel deformation zones, rock units and ultimately critical structures/volumes are listed in Appendices 2 and 3. A summary of significant components to support identification of structures that constitute potential risks for secondary movements and rock volumes that significantly limits the thermal output from the deposited canisters are presented in Figure 5-21 and Figure 5-22. Identification of potentially critical structures that are at risk of developing shear exceeding the canister failure criterion is done by analysis of properties that show evidence of large displacements. Whereas displacements can be recognized in individual borehole/tunnel intersections, a verification of size requires large scale exposures or multiple observations (e.g. excavations for the operational areas or underground facility parts), or an analysis of the hydraulic connectivity from several individual observations in tunnels/boreholes as a proxy for size.

For the site descriptive modelling in Forsmark and Laxemar, the SHI focused on possible deformation zones that could vary in size (length) from just under 1 000 m and upwards (cf SKB 2008). During the subsequent SFR extension project SDM-PSU (SKB 2013), increased data density made it possible to include deformation zones with trace lengths down to 300 m. The latter is largely equivalent to the size of the structures defined as potentially critical for seismic reactivation that could cause damage to the canister, which includes continuous single fractures and minor deformation zones with a circular radius exceeding approximately 200 m (cf Fälth et al. 2016), see Section 5.4.1.

The typical parameters listed by Cosgrove et al. (2006) for identifying large fractures need to be developed for the conditions specific to Forsmark. An analysis made for ONKALO by Nordbäck (2014), showed that the most typical properties of fractures with a diameter > 50 m are slickensides, thick fillings of certain minerals, water leakage and associated alteration, but also orientation and rock type are important indicators. However, to do this analysis at Forsmark, there remains a need to assemble and analyse data from underground tunnels and shafts.

The identification strategy for the development of the deposition areas, where investigations, interpretation and modelling are planned in campaigns that comprise 4–6 deposition tunnels, follows the approach presented above for modelling of deformation zones and domains (see Section 5.4.6 and 5.5).

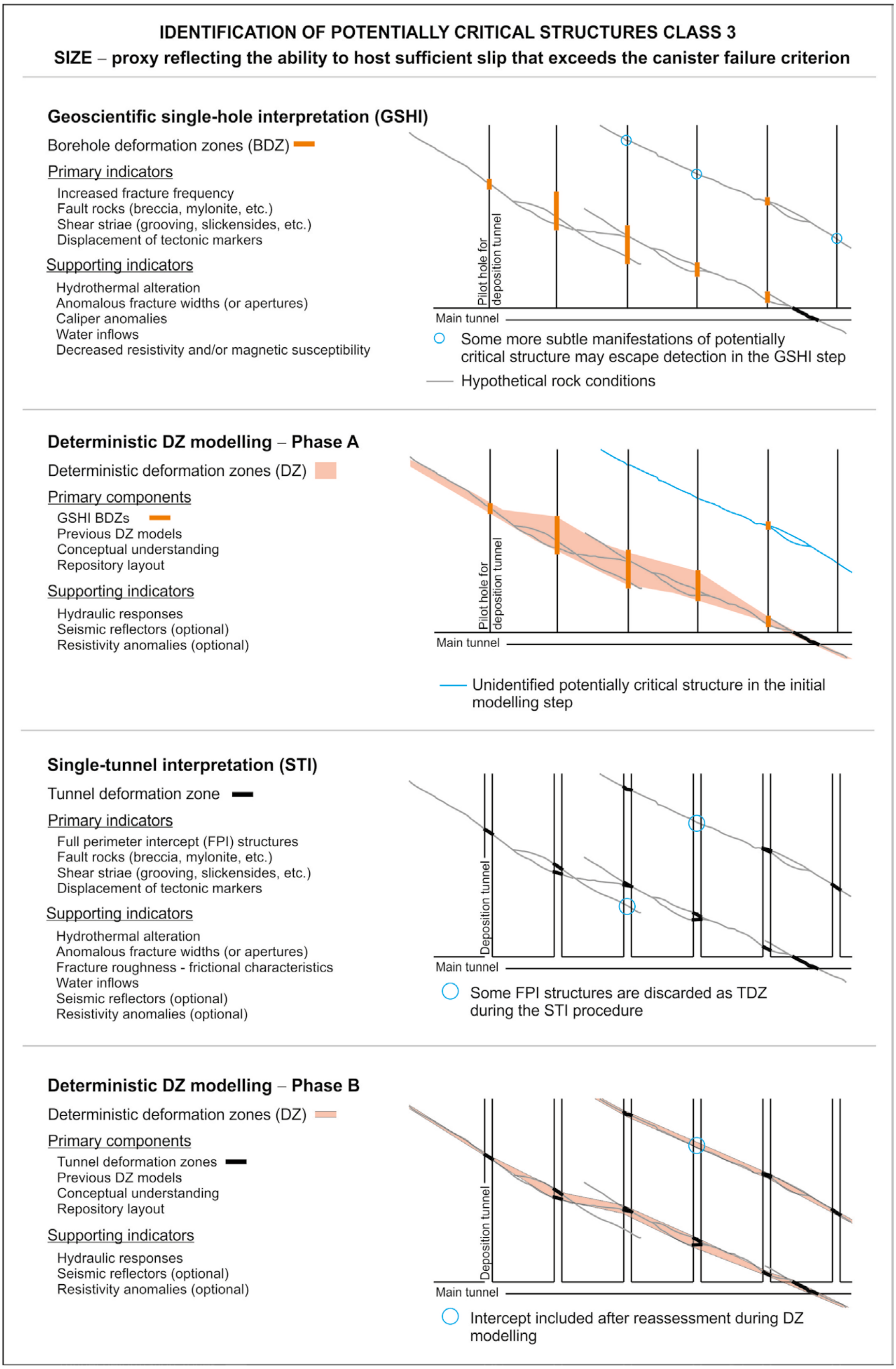


Figure 5-21. *Illustration of the stepwise process for identification of critical structures class 3 that constitute potential risks for secondary movements in canister positions. Significant indicators and components to support identification are listed, along with examples of inferred geometries based on borehole and tunnel intersection of two critical structures.*

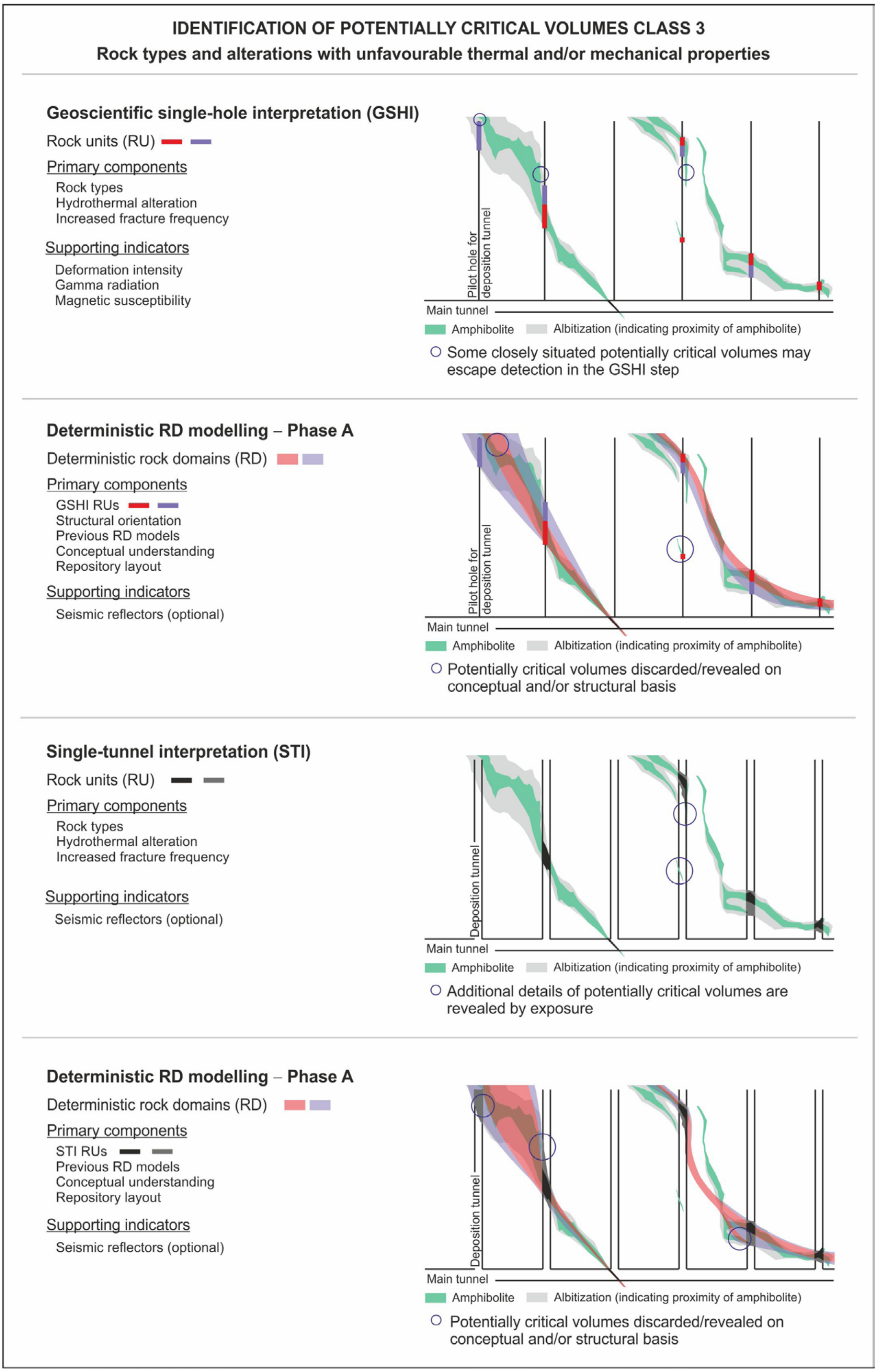


Figure 5-22. *Illustration of the stepwise process for identification of critical volumes of class 3 that include rocks and alterations with unfavourable thermal and/or mechanical properties. Significant indicators and components to support identification are listed, along with examples of inferred geometries based on borehole and tunnel intersection of two folded amphibolite dykes and associated albitization.*

6 Uncertainties in the geological modelling process

This chapter focuses on assessing uncertainties considered to have significant implications for the 3D geological modelling. The term “uncertainty” can have quite different meanings in different contexts. The proposed methodology quantifies uncertainty of the data sources used to model an object, as well as providing estimates of the quality of the interpretation in three dimensions (Sections 6.1 to 6.3). Although references to uncertainty in primary data are discussed, the methodology builds on several levels of pre-interpretations of data, such as estimates of lineament and reflector quality, that are made in steps prior to the actual modelling. This is also true for estimates of borehole/tunnel deformation zones identified during the GSHI and STI interpretations.

Section 6.4 assesses uncertainty of the potential variability in size of deformation zones. DFN methodology is proposed to stochastically extend the structure beyond the deterministic geometry, while maintaining geological concepts and constraints.

It is important when making 3D geological interpretations to weigh between data uncertainty and conceptual uncertainty. The latter involves assessing alternative models to evaluate different concepts and scenarios (see Section 6.5).

Munier et al. (2003) and Andersson (2003) have previously described uncertainty and confidence building in site descriptive modelling. In Stephens et al. (2007), uncertainty was quantified in terms of spatial positions along boreholes and locations of lineaments and reflectors. There it was concluded that the uncertainty calculated for the spatial positions of boreholes drilled from the ground surface in all three dimensions generally increases somewhat with depth and is more significant in the horizontal plane (x-y) than in the vertical (z) direction. The estimated uncertainty of the position of both rock units and possible deformation zones in the boreholes does not exceed ca 30 m in the horizontal plane. In most cases, the uncertainty is less than 10 m in the horizontal plane and less than 6 m in the vertical direction.

Stephens et al. (2007) concluded that estimates for the uncertainty in the position of boreholes can be compared with an uncertainty of ± 20 m and ± 10 m for the position of low magnetic lineaments at the surface, on the basis of airborne (helicopter) (Isaksson and Keisu 2005) and ground magnetic (Isaksson et al. 2006a) data, respectively, and an uncertainty of ± 15 m for the position of a seismic reflector (Cosma et al. 2003). Thus, the uncertainties in the position of boreholes seem to be approximately on the same order of magnitude as the uncertainty in the position of the geophysical entities, which have been used continually during the SDM Site geological modelling work. Although this uncertainty has minor consequences for the estimation of dip, and to some extent also the modelled thickness of deformation zones, the implications of these uncertainties for the geological modelling work are judged to be of minor significance compared to other more interpretative factors such as the coherence between different geological observations and their interpolation or extrapolation. This suggests that a more thorough evaluation of uncertainties in geological modelling should be directed to towards interpretative uncertainties. The ambition is to quantify these uncertainties, such that mitigation measures (see further below) can decrease the uncertainty. Furthermore, the use of relatively short pilot holes and eventually tunnel data imply that spatial uncertainties will be minimal.

This chapter will highlight areas where uncertainties can be significant in the deterministic geological modelling methodology, which is largely dependent on subsurface information from boreholes and tunnels and will attempt to give directions to useful mitigation measures for the modeller.

6.1 Quantification of confidence for modelled deformation zones

During the surface-based site descriptive modelling, the term “confidence in existence” was used to communicate the total assembly of motives, indications, and arguments in support for the existence of a modelled object. The primary basis for this estimate was an integrative process addressing the relative impact of various data sources, according to the principle that direct geological observations increased the confidence in the interpretation of a given object.

With the current updated methodology, the former confidence concept has been revisited to capture additional aspects, particularly the modelling decisions related to object geometry. The proposed approach includes four confidence categories, where each is divided in two subcategories (Table 6-1).

Table 6-1. Categories and subcategories used for quantification of confidence for modelled deformation zones.

Category	Subcategory
Interpretation	Data source Results of interpretation
Information density	Number of observation points Distribution of observation points
Interpolation	Geometry Geological indicators
Extrapolation/Truncation	Strike direction Dip direction

Each subcategory has different impacts on the overall confidence assessment. Evaluation of confidence for each subcategory is addressed by a three-level confidence scale, where 1 = low, 2 = medium and 3 = high. A total relative confidence for a modelled object is then achieved by summing the confidence estimates for each individual subcategory. With eight subcategories between the four main categories, the total confidence ranges between 8 and 24. This quantitative approach provides a relative scale of confidence, which enables comparison between different modelled objects, such as deformation zones. The degree of confidence can be visualised by means of colour coding of the modelled geometries. As the subcategories reflect a wide span of uncertainties, it is not considered useful to introduce different weighs to the various categories. Instead, the subcategories provide a relative scale of confidence that can be used in the comparison of different structures.

To avoid ambiguity, the application of this system requires clear principles. Details for assessment of confidence within each category are presented in the sections below.

6.1.1 Category – Interpretation

This category is intended to reflect the information quality in the various data sources used and includes the following two subcategories: (1) data sources and (2) results of interpretations.

Subcategory – Data source

This is roughly equivalent to the previously used term “confidence in existence”.

Modelled structures are primarily based on the following data sources:

- Tunnel and outcrop mapping
- Borehole logging
- Lineaments
- Seismic reflectors

Direct geological observations in outcrops, tunnels and boreholes are considered more reliable than indirect indications shown by geophysical data, with a possible allowance for alternative interpretations. Additionally, more extensive observation windows provided by outcrops and tunnels are regarded as a sounder basis for identification than a single observation in a borehole. Based on these assumptions, the following principles are applied to confidence estimates of the subcategory data source:

– Low	Lineaments and seismic reflectors
– Medium	Borehole observations
– High	Outcrop or tunnel observation

A modelled object is usually based on data from more than one source. In such a case, the assessment will be based on the source with the highest degree of confidence. The principle can be illustrated by an example of a deformation zone based on a lineament and four borehole intercepts, which is assigned confidence level 2 (medium). By adding an outcrop or tunnel observation, the confidence level of the zone can be increased to 3 (high).

Subcategory – Results of interpretations

Raw data require a prior step of processing and analysis (here collectively referred to as interpretation) before they can be used within the framework of deterministic modelling. Each object identified during these successive interpretation steps is assigned a confidence level by the scale 1–3 according to the following:

- Lineaments are based on the quality in their interpretations, see Isaksson et al. (2006b).
- Seismic reflectors are based on a ranking made in the geophysical interpretation, see Juhlin and Palm (2005). The rank "indicates how certain the observation of each reflection is on profiles that the reflection is observed on; definite (1), probable (2), possible (3)". When used for confidence estimates of modelled objects, this scale is reversed such that definite = high (3), probable = medium (2) and possible = low (1).
- Geologic single-tunnel interpretation is based on the confidence of the identified tunnel deformation zone, see Appendix 3.
- Geoscientific single-hole interpretation is based on the confidence of the identified borehole deformation zone, see Appendix 2.

Confidence estimates of modelled objects shall describe the best defined intercept/lineament/reflector in the data source with the highest degree of confidence. As an example, for a deformation zone based on a lineament and four borehole intercepts, it is the interpretation with the best quality that defines the confidence estimate for the object, in this case the BDZ identified by the GSHI. The difference between cored and percussion boreholes is, to some extent, captured by this approach, since BDZs in percussion boreholes are typically identified with a lower degree of confidence.

The two confidence estimates for the interpretation category are exemplified in Table 6-2 by analysing four deformation zones of the site descriptive model (see Stephens and Simeonov 2015).

Table 6-2. Example of confidence estimates of the interpretation category, illustrated using confidence levels transferred from the interpretation step of four different deformation zones of Forsmark model version 2.3.

Basis for deformation zone modelling	Confidence assigned in the interpretation step	Confidence estimates for category interpretation	
		Data source	Interpretation
ZFMENE0401A		2	3
Lineament MFM0401	3		
Lineament MFM0401G0	3		
Borehole HFM13 DZ1	2		
Borehole KFM05A DZ3	3		
ZFMNNE0929		1	3
Lineament MFM0929	3		
ZFMENE0062A		3	3
Lineament MFM0062	3		
Lineament MFM0062G0	3		
Borehole HFM25 DZ4	2		
Borehole HFM25 DZ5	2		
Outcrop AFM001243	3		
ZFMB23		1	3
Seismic reflector B2	3		
Seismic reflector B3	3		

6.1.2 Category – Information density

This category is intended to communicate the significance of information density and include two subcategories: (1) number of observation points, and (2) their spatial distribution within a modelled object. Both subcategories are based on quantitative data, where the bounds between different confidence levels are set to capture the range of information density provided by data from the ground surface, seismic reflectors and existing boreholes, in combination with a repository layout. Based on this, confidence concerning data density is addressed by the following principles:

Subcategory – Number of observation points

– Low	< 2 observation points
– Medium	2–3 observation points
– High	≥ 4 observation points

Subcategory – Distribution of observation points

– Low	Large distance between points and/or two observation points or less
– Medium	A group of clustered observation points and at least one or more outliers
– High	Dominated by evenly distributed observation points with max one outlier

Each individual intercept (lineament, reflector, borehole, or tunnel) is regarded as a separate observation. More specifically, lineaments and seismic reflectors are treated as one observation, regardless of whether a structure is based on an individual lineament or reflector or a combination of several lineaments or reflector elements. The minimum distance of 20 m is intended to appropriately evaluate observations that describe structures of interest for the safety of the repository, i.e. critical structures with radius of 200 m or more. If observations are closer than 20 m they count as a single observation. In order for a borehole intercept to be considered an observation point, there has to be geological indications that support the existence of a deformation zone.

The principle of confidence assignment based on the distribution of observations is illustrated in Figure 6-1. This assignment is intended to qualitatively capture how well observation points constrain the interpreted object. Structures based solely on lineaments or seismic reflectors should all be assigned low confidence (Figure 6-1F). An exception is where direct geological observations and indirect observations (i.e. lineaments or seismic reflectors) coincide spatially, for example a borehole intercept along a seismic reflector or an outcrop along a lineament. In such cases, lineament or seismic reflectors are not regarded as observations and only direct geological observations are included.

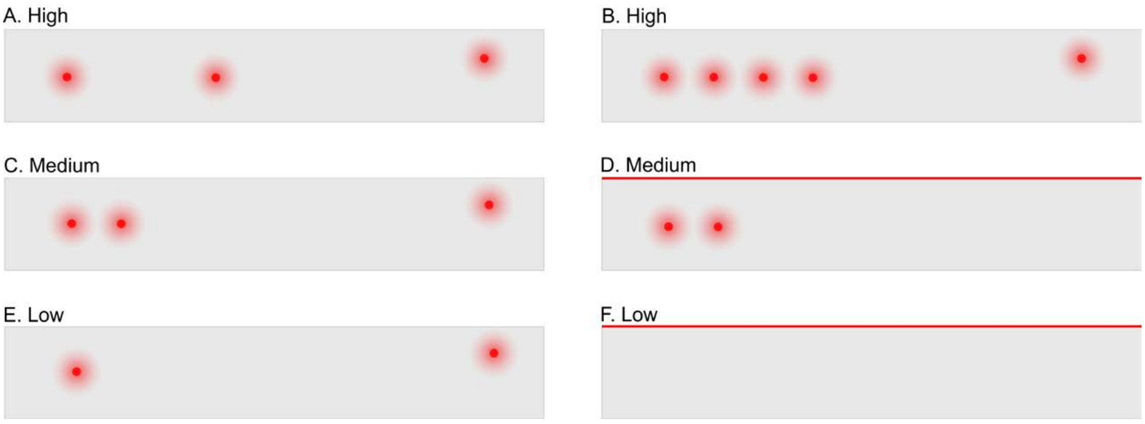


Figure 6-1. *The principle of confidence assignment based on the distribution of observation points illustrated by schematic views of highly simplified deformation zones (grey rectangles). Example A shows an even distribution of observation points (red dots). Locally increased density, as in example B, does not affect the confidence level. Examples C and D show clustered observation points with one outlier, where the lineament (red line) in example D counts as an outlier. Example E shows two observation points and example F a single lineament.*

6.1.3 Category – Interpolation

The purpose of this category is to quantify the motives for matching different observations to a specific geological object. Interpolation can be based on two different subcategories: (1) geometry and (2) geological indicators. However, the two subcategories are mutually dependent in the sense that geometrical correlation is necessary to allow geological correlation, and vice versa.

Subcategory – Geometry

The geometrical subcategory concerns primarily the spatial arrangement of observations at the ground surface, in boreholes and in tunnels, but also the structural trend obtained by analysis of the orientation patterns of brittle and brittle-ductile structures. The confidence level of the Geometry subcategory depends solely on the alternatives available for interpolation, where an increased number of alternatives lower the confidence level as follows:

– Low	None or more than two alternative observations exist
– Medium	Two alternative observations exist
– High	One strong observation alternative exists

Subcategory – Geological indicators

The second part of the interpolation category, which covers the geological basis for interpolation, is more qualitative, with indicators such as fracture fillings, alterations, thickness, water inflow and deformation intensity. Considering the spatial heterogeneity along virtually all deformation zones, interpolation can rarely rely on a single indicator. Instead, high confidence interpolation requires evaluation of the overall geological character. Based on this, the following principles guide the confidence estimates of interpolation on geological basis:

– Low	Only indirect support by hydraulic or geophysical data
– Medium	Some discrepancies in the geological data or geological character
– High	Interpolation is supported by key geological parameters

Confidence assignments for the interpolation category can be illustrated by a schematic example shown in Figure 6-2.

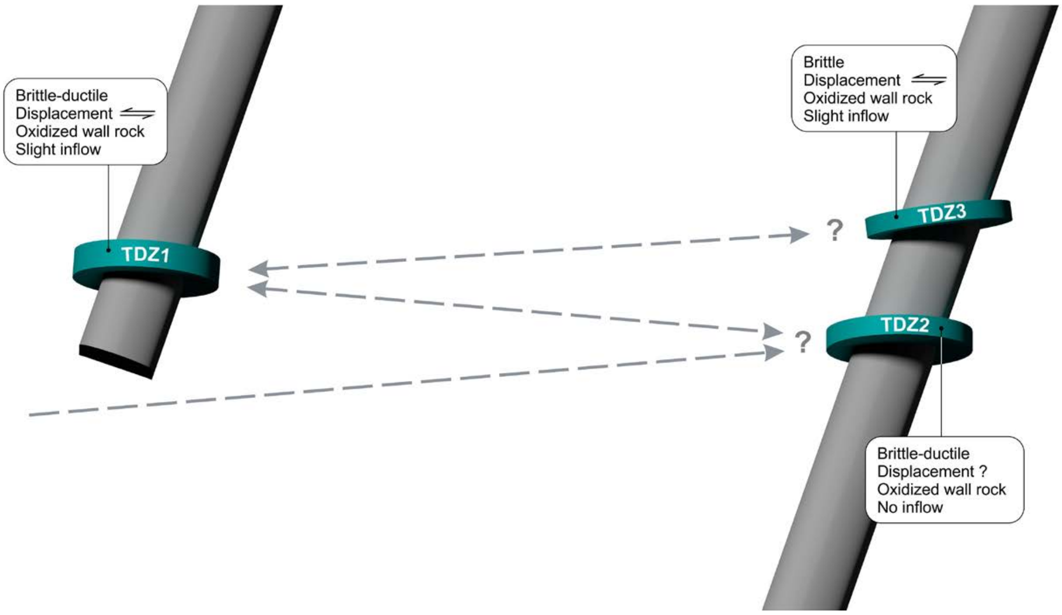


Figure 6-2. *Schematic illustration of three tunnel deformation zones (TDZ) identified along two deposition tunnels. Interpolation between TDZ1 and TDZ2 alternatively TDZ1 and TDZ3 is assigned a medium confidence level both regarding geometry (two alternative observation points) and geological support (some discrepancies in the geological character), regardless of choice.*

6.1.4 Category – Extrapolation/Truncation

The basic idea of the category extrapolation/truncation is to evaluate the arguments to support extrapolation beyond their observation points in terms of confidence. Since the motives for extrapolation are strongly dependent on direction, especially for vertical to steeply dipping structures, the category is separated into two subcategories: strike (horizontal) and dip direction. The concept behind the category is also applicable on sub-horizontal to gently dipping structures, though normally, the estimates will be identical for both strike and dip as surface information is not generally available.

For structures limited to the subsurface, the confidence assignments of this category are largely based on the principles for extrapolation presented in Section 5.4.7 (cf Figure 5-13), whereas assignments of confidence for structures intersecting the ground surface primarily rely on the associated lineament pattern. In detail, the confidence assignments concerning extrapolation/truncation can be summarised into the following principles for the subcategories strike and dip direction:

Subcategory – Strike direction

– Low	No indications or constraints (alternative 4 in Figure 5-13, i.e. horizontal extrapolation to the equivalence of 1/3 of th maximum intercept distance)
– Medium	Inferred truncation against other structures and/or minimum extrapolation length (radius > 200 m) defined by kinematic indicators (alternative 3 in Figure 5-13) and/or very distant geometrical controls from tunnels or boreholes (> 1/3 of the maximum intercept distance)
– High	Indicated and constrained by the pattern of surrounding lineaments or high confidence zones (alternative 2 in Figure 5-13), alternatively by strong geometrical control from surrounding tunnels and boreholes (alternative 1 in Figure 5-13)

Subcategory – Dip direction

– Low	No indications (alternative 4 in Figure 5-13, i.e. vertical extrapolation to the equivalence of 1/3 of the maximum intercept distance or to the extrapolation constraint volume)
– Medium	Inferred truncation against other structures and/or minimum extrapolation length (radius > 200 m) defined by kinematic indicators (alternative 3 in Figure 5-13)
– High	Geometrical control by surrounding tunnels and boreholes (alternative 1 in Figure 5-13)

The confidence level for each subcategory is defined by the part that provides the least confident extrapolation, in accordance with the example illustrated in Figure 5-14.

6.1.5 Tabular summary of confidence for deformation zones

The assembled evaluation of confidence in the modelling of a deformation zone is presented in a summary table (cf Table 6-3), which is stored in the object description library (cf Figure 5-3). This enables a rapid evaluation of the total confidence of a zone or may be used to evaluate certain aspects pertaining specific categories. Simple colour coding of confidence can also be used in the modelling tool to sort and visualise uncertainty aspects in the model.

Table 6-3. Tabular summary of confidence for deformation zones. Evaluation example for four deformation zones described in SDM-Site (Stephens et al. 2007). Colour scale examples are given for individual or total confidence measures.

Category	ZFM0159	ZFMNNE0929	ZFMB23	ZFMB1
INTERPRETATION				
Data source: 1. Lineaments and seismic reflectors 2. Borehole observations 3. Outcrop or tunnel observations	3	1	1	2
Results of interpretation: Assigned confidence level is based on the highest level of the individual interpretation	3	3	3	3
INFORMATION DENSITY				
Number of observation points: 1. ≤ 2 observation points 2. 2–3 observation points 3. ≥ 4 observation points	3	1	1	1
Distribution of observation points: 1. Large distance between points and/or two observation points or less 2. A group of clustered observation points and at least one or more outliers 3. Dominated by evenly distributed observation points with max one outlier	2	1	1	3
INTERPOLATION				
Geometry: 1. None or more than two alternative observation points exist 2. Two alternative observation points exist 3. One strong observation alternative exists	2	1	1	3
Geological indicators: 1. Only indirect support by hydraulic or geophysical data 2. Some discrepancies in the geological data or geological character 3. Interpolation is supported by key geological parameters	3	1	1	1
EXTRAPOLATION/TRUNCATION				
Strike direction: 1. No indications, i.e. horizontal extrapolation to 1/3 of the maximum intercept distance 2. Inferred truncation against other structures and/or minimum extrapolation (radius > 200 m) defined by kinematic indicators 3. Indicated and constrained by the pattern of surrounding lineaments or high confidence zones alt. to surrounding boreholes/tunnels	3	3	2	2
Dip direction: 1. No indications, i.e. extrapolation in the dip direction to 1/3 of the maximum intercept distance 2. Inferred truncation against other structures and/or minimum extrapolation (radius > 200 m) defined by kinematic indicators 3. Geometrical control by surrounding tunnels and boreholes	1	2	2	2
SUMMARY	20	13	12	17

Summary scale	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

6.2 Quantification of confidence in modelled domains

Rock domains defined during the preceding site descriptive modelling were all assigned a "confidence in existence" both at the ground surface and at the base of the model volume, using the three levels, low, medium and high. This concept encompasses occurrence, geometry and the arguments in support for the extension to the base of the model volume (cf SKB 2005). The projection of rock domain boundaries towards depth has predominantly made use of structural data from surface outcrops, with supplementary structural data from boreholes, where such exist. Based on this, the following guidelines have been applied to assign the level of confidence for rock domains:

- High outcrop coverage and access to magnetic data are two factors that have yielded well-founded boundaries on the bedrock geological map, and thereby a high confidence in existence at the ground surface for the corresponding domains.
- Only domains with deficiency of those data, for example due to coverage by the sea, are assigned a medium confidence level at the ground surface.
- Domains with frequent structural data (tectonic fabric) from the ground surface outcrops are assigned a medium level of confidence at the base of the model volumes, based on the current understanding of the tectonics in the area. Domains which virtually lack structural data from the ground surface outcrops (mainly due to sea coverage) are assigned a low level of confidence.
- The existence of compositional and structural data from deep, cored boreholes have been assigned a high confidence level at the base of the local model volume (i.e. at −1 100 m) and a medium level of confidence below that to the base of the regional model volume (i.e. at −2 100 m).

The approach for assigning confidence levels for the large-scale rock domains was developed during the site descriptive modelling and has provided useful input to downstream users. However, an alternative approach will be needed for assigning confidence levels to subordinate rock domains that are only encountered at depth (such as the trend of brittle/ductile structures or occurrences of amphibolite, cf Section 5.5).

The fact that the modelling approach for small-scale rock domains and deformation zones (cf Section 5.4.6) basically rely on the same principles is an argument in support of a similar system for confidence estimates. However, differences that needs to be captured by the approach are, for example, that degree of homogeneity can be the basis for identification as well as the fact that the domains are space-filling objects. Following this, the confidence estimates for small-scale rock domains includes four categories, which are all varieties of those to be applied for deformation zones (see Section 6.1). Details of the categories and the corresponding subcategories are provided in Table 6-4.

Table 6-4. Criteria for confidence estimates of the geometry of rock domains.

INTERPRETATION
Data source: 1. Only indirect support by geophysical data 2. Borehole observations 3. Outcrop and/or tunnel observations
Results of interpretation: Assigned confidence level is based on the highest level of the individual interpretation
INFORMATION DENSITY
Number of observation points: 1. ≤ 2 observation points 2. 2–3 observation points 3. ≥ 4 observation points
Distribution of observation points: 1. Large distance between points and/or two observation points or less 2. A group of clustered observation points and at least one or more outliers 3. Dominated by evenly distributed observation points with max one outlier
INTERPOLATION
Geometry: 1. None or more than two alternative observation points exist 2. Two alternative observation points exist 3. One strong observation alternative exists
Geological indicators: 1. Only indirect support by geophysical data 2. Some discrepancies in the geological data or geological character 3. Interpolation is supported by key geological parameters
EXTRAPOLATION/TRUNCATION
Horizontal direction: 1. No indications, i.e. horizontal extrapolation to 1/3 of the maximum intercept distance 2. Inferred truncation against other known domains or tectonic boundaries 3. Indicated and constrained by the pattern of surrounding domains or tectonic boundaries and/or to surrounding boreholes/tunnels
Vertical direction: 1. No indications, i.e. vertical extrapolation to 1/3 of the maximum intercept distance 2. Inferred truncation against another domain or tectonic boundary 3. Indicated and constrained by the pattern of surrounding domains or tectonic boundaries and/or to surrounding boreholes/tunnels

6.3 Confidence in the geological properties of 3D objects

Properties and characteristics are defined in the modelling process. The properties that are used in the assignment of confidence levels for modelled deformation zones include the following:

- Deformation style
- Sense of displacement
- Alteration
- Fracture character

An explicit example of this assessment is described in Appendix 4 (Figure A4-1). The process stipulates that estimates of confidence are set by a three-level confidence scale (low, medium and high) and shall be included for appropriate geological characteristics as well as for quantitative measures of systematic errors, such as orientation biases in fracture measurements. The principle is that direct geological observations furnish for high confidence levels. However, properties most commonly emanate from a limited number of observation points and must therefore be treated with extreme care when extrapolated to the rock mass beyond the observation points. Also, the degree of homogeneity among the data affects the resulting confidence level; for instance, a high degree of homogeneity requires fewer observation points to reach a predictable variation, and hence a high confidence level. The confidence level for geological properties is obviously highly dependent on the data source, interpretation, number of and distance between observation points, etc. Capturing these factors in a rational working process requires both generalisations and strict guidelines.

The approach presented below is largely adopted from the foregoing site descriptive modelling (Stephens et al. 2007) and follows a concept where the confidence level is reduced due to various data limitations. For a particular property in a deformation zone object, the adjustment from high to a lower level of confidence, includes the following:

- Assignment of a medium level of confidence to the estimates of the fracture character if the heterogeneity of the various underlying properties defining the fracture character varies, as well as the distance between observation points.
- Assignment of a low level of confidence to the assessment of the style of deformation and fracture frequency in zones intersected solely by percussion boreholes, since particularly these data are of insufficient quality.
- Assignment of a low level of confidence to the estimates of thickness where borehole and/or tunnel intersections are lacking.
- Assignment of a medium level of confidence to the estimates of length for zones that extend outside the regional model volume, or that are coupled to a lineament where some modifications have been made to the length of the lineament or other assumptions have been made in connection with the modelling work.
- Assignment of a medium level of confidence to the judgement that alteration is present along a zone when this is based solely on the character of a magnetic lineament.
- Assignment of a low or medium level of confidence to the estimates of the sense of movement along zones, when shear striae data emanate from a restricted number of observation points. In the cases where only a few data (< 9) are available from a borehole (or boreholes), a low level of confidence has been provided. Where there is a higher quantity of shear striae data from the borehole(s), a medium level of confidence has been assigned.

The range, mean and standard deviation values of properties will be available for most rock types within the rock mass in proximity to the repository. The remaining uncertainty concerns the relative occurrence of different subordinate rock types in a specific rock domain. An intersection with the ground surface often allows qualitative estimates of rock type properties from outcrop data. Quantitative estimates are however strongly dependent on subsurface data from boreholes and tunnels. On this basis, adjustment from high to a lower level of confidence for a particular property in a rock domain object, includes the following:

- Assignment of a medium level of confidence to the estimates of the internal rock type distribution and petrographical properties based on a restricted number of observed intersections or intercepts showing a high variability.
- Assignment of a low level of confidence to the estimates of rock type distribution intersected solely by percussion boreholes, since particularly these data are of insufficient quality.
- Assignment of a low level of confidence to the variation of rock type distribution at depth where borehole and/or tunnel intersections are lacking.

6.4 Addressing uncertainty in deterministic modelling through DFN

A comprehensive DFN modelling methodology is presented in detail in Selroos et al. (2022). Deterministically modelled structures are an integral part of DFN modelling and some aspects of uncertainty in the geological modelling can be assessed using DFN. It is important to note that the geological modelling methodology will supply downstream users with self-contained geometries and descriptions that can be used as presented. However, these geometries and descriptions can also be used in very different ways in other modelling concepts depending on their assumptions and needs. Some concepts may need all the modelled geological complexity, such as variable thickness of zones and detailed characterization of each object, while others may only need simplified geometry or certain aspects of the characteristics.

This section addresses a few approaches of how geometrical uncertainty in the geological model can be assessed using DFN methodology with comparable, but stochastic, geometrical representations of deterministic structures. The geological modelling methodology prescribes how extrapolation of deterministic structures is made, based on a series of modelling principles. These principles constrain the extrapolation to a distance within which the geologist can have reasonable confidence in the validity of the modelled geometry. Therefore, structures will be deterministically modelled up to their assumed minimum geometric extent which means that the potential extent (size) of deterministic features may be larger.

To assess the uncertainty of the potential variability in size of deformation zones that do not have geologically specified spatial constraints, DFN methodology can be used to stochastically extend the structure beyond the deterministic geometry. This stochastic variation of size, together with the deterministic geometry, can be included in the DFN modelling, which also describes the fracture network in the rock mass around the repository.

6.4.1 Deterministic, semi-stochastic and stochastic structures

DFN modelling will be used to simulate the fracture network throughout the rock mass and will account for the full-size spectrum of small fractures up to the largest observable features in the region. On the other hand, deterministic modelling will only include structures interpreted to be larger than 200 m equivalent radius which can be observed in boreholes, tunnels or at the ground surface. The interface between the DFN and the deterministic models will thus exist in the larger than 200 m size range, as illustrated in Figure 6-3. Also, the coverage of deterministically modelled structures will be different in different areas as follows:

- Structures modelled during SDM-site were constrained to a regional model volume as explained by Stephens and Simeonov (2015). This model volume contained structures longer than 3 km of surface trace length. SDM-site deterministic structures, with a trace length of 1 km or more at the ground surface, were modelled inside a model volume encompassing the site.
- Recently, deterministic structures, with a ground surface trace length of 5 km or larger, have been modelled in the catchment area around Forsmark.
- Deterministically modelled structures based on subsurface observations will cover mainly the sub-volume around the repository.

As the constructions in the Forsmark area proceeds, deterministic modelling will identify and describe structures down to the equivalent circular radius size of 200 m adjacent to the underground openings. However, beyond the limits of the underground excavation it is expected that other structures of similar size exist, but which cannot be directly observed due to lack of data. The DFN model also needs to stochastically simulate structures larger than 200 m equivalent circular size radius that are not intersecting any part of the underground openings, boreholes or the surface.

Thus, the uncertainty in the spatial extent of deterministically modelled deformation zones is suggested to be modelled semi-stochastically, whereas the existence of deformation zones in the rock mass where no observations exists needs to be handled purely by stochastic methods (described in detail in Selroos et al. (2022)). DFN modelling methodology also allows for representing the deterministic structures in other ways, such as swarms of fractures, channel or pipe networks, which is covered by Selroos et al. (2022).

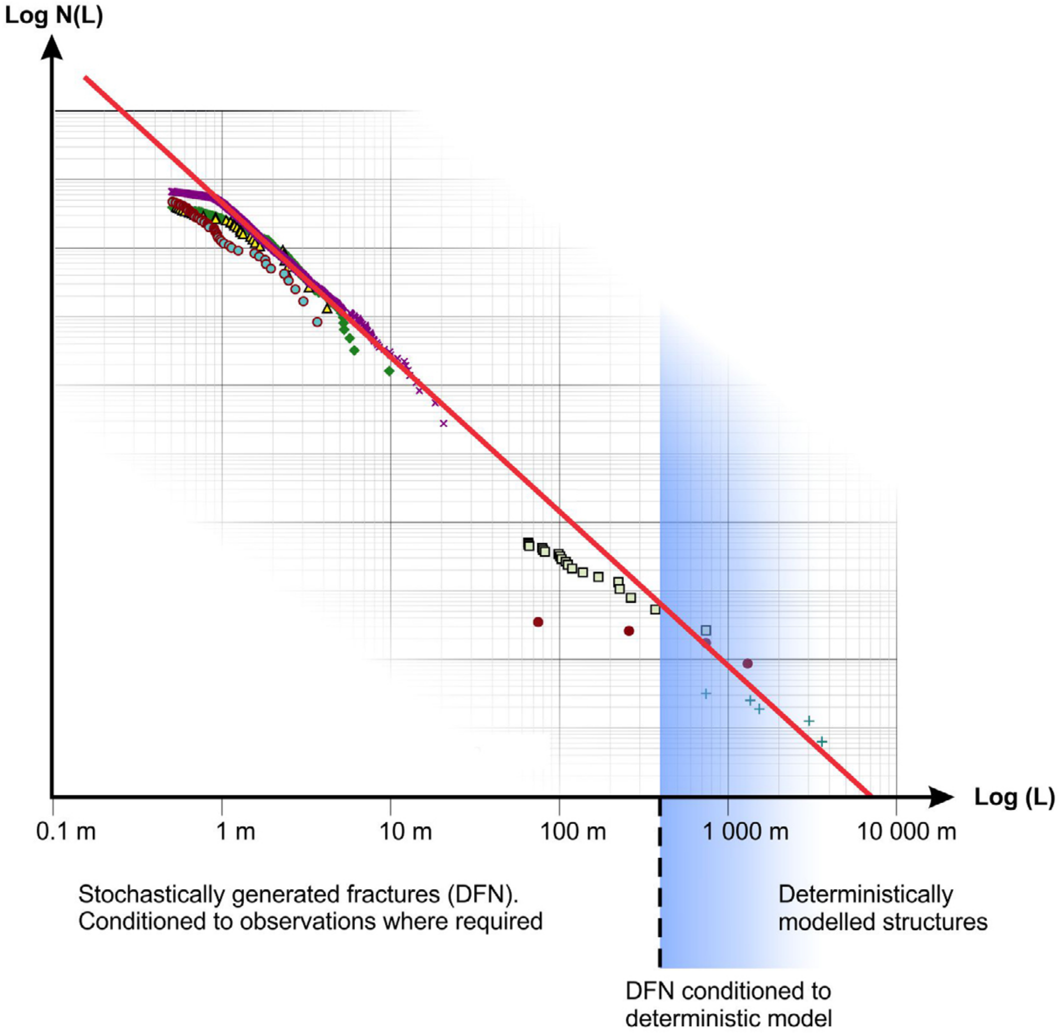


Figure 6-3. *Counter complementary cumulative plot of trace length measurements at all available scales in Forsmark showing the size interval interface between the stochastic and the deterministic models (modified from Figure 9-19 in Fox et al. 2007).*

6.4.2 Structures based only on subsurface data

Section 5.4.7 describes the principles for geometric extrapolation of structures based only on subsurface data. In the description of each modelled structure (see example in Figure A4-1 in Appendix 4), the geologists will state how the boundaries of the geometry is constrained by terminations against other structures, the surface as well as observed intersections with outcrops, boreholes or tunnels, as illustrated in Figure 6-4. Constraints are given in four principal directions: upper and lower bounds as well as in and opposite to the strike direction. If there is no available information in one or more of these general directions, the modelled geometry will be marked as unconstrained as exemplified in Figure 6-4. Stochastic assessment of size is only proposed in unconstrained directions as illustrated in Figure 6-5.

GEOMETRICAL CONSTRAINTS		Constrained
Upper	Ground surface	Yes
Lower	−280 m	No
Strike direction	ZFMENE0159A	Yes
Opposite strike direction	ZFMENE1061A, ZFMNNW1205A	Yes
Observed intersections	AFM001393, KFM08B, KFM13, KFM21	

Figure 6-4. *Geometrical constraints given for each deterministically modelled structure. Excerpt from Figure A4-1.*

It is suggested that the variation in size is addressed through semi-stochastic fracture generation for structures that have one or more unconstrained directions. There are several approaches for such simulations, depending on the purpose and concepts that are most appropriate for the DFN modelling. Deterministically modelled geological structures may be complex geometrical objects, with undulating curvature to match several observations in boreholes, tunnels, and surface lineaments, as well as having non-rectangular shapes from terminations against other structures. However, during SDM-Site, the geologists generally used the curvature of the surface lineament in the depth extrapolation of each structure combined with matching the surface to observations in boreholes. Maintaining exact geometry of the intersections with all observations will require that variations in size are simulated with non-planar semi-stochastic features. Depending on the purpose of the DFN model, planar geometries may be a reasonable simplification to study specific issues, such as effects of connectivity in the fracture network system. From the standpoint of addressing uncertainty in the geological modelling, two broad approaches to semi-stochastic features are envisioned:

- non-planar features matching the observations, using a similar rectangular geometrical concept as used in SDM-Site, and
- simplified planar features (any shape) minimising the mismatch to observations, but with the ability to extend in all desired directions.

Non-planar semi-stochastic features could be simulated using a similar strategy as illustrated in Figure 6-5a. The illustration shows a non-planar semi-stochastic feature that extends in a rectangular fashion beyond the deterministic geometry in the geologically unconstrained directions while maintaining the deterministic curvature as well as the defined geological constraints. Multiple realisations of the zone can be created maintaining curvature as well as geological constraints such as the presence or absence of intersections with tunnels, ground surface, or boreholes. The same approach can be used for simulating semi-stochastic features intersecting the ramp, the shafts and the rock caverns of the central area as well as the deposition areas. Each variation in colour illustrates a stochastic realisation with different size. This is similar to the concept of site descriptive modelling based on ground-surface data (see Section 5.4.2) and would fulfil the need for addressing uncertainty in unconstrained directions of the deterministically modelled geometry.

A planar semi-stochastic approach, as illustrated in Figure 6-5b, could be used to simulate variations in size while maintaining the defined constraints at the expense of minimising deviation from observations. Each circle illustrates stochastic realisations with different size and points of origin. This planar concept may not match observations exactly but could simulate different geometrical shapes and would fulfil the need for addressing uncertainty in unconstrained directions of the deterministically modelled geometry.

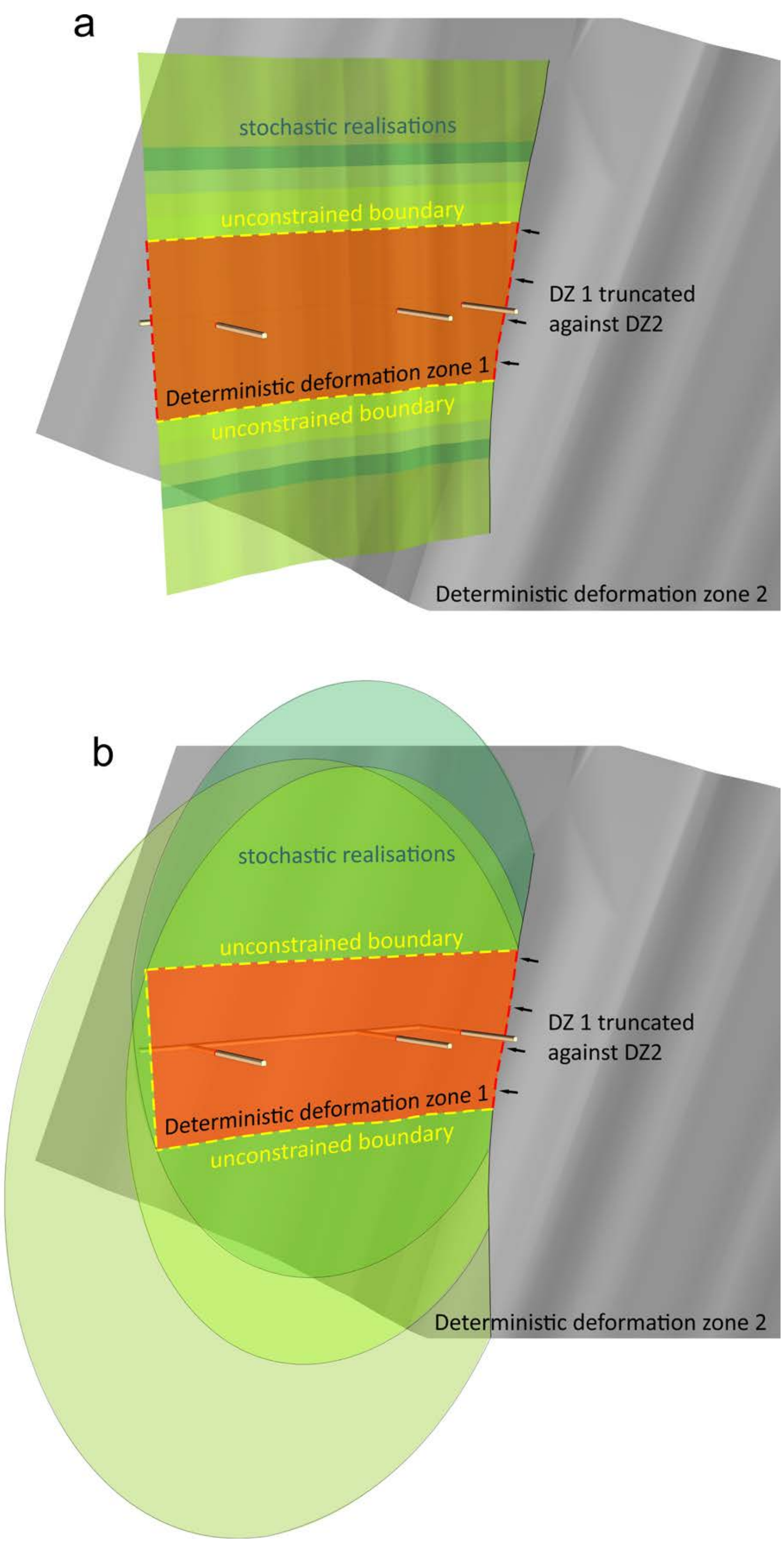


Figure 6-5. *Two conceptual illustrations of semi-stochastic modelling of a deformation zone intersecting three tunnels and terminates against a known deformation zone. (a) Concept of non-planar growth matching the observations, using a similar approach to the concept of site descriptive modelling based on ground-surface data (see Section 5.4.2). (b) Concept of simplified planar features (any shape) minimising the mismatch to observations, but with the ability to extend in all desired directions.*

Other concepts, for example using semi-stochastic planar or non-planar fracture growth from seed-points, or other combinations of the two approaches above, could be used if technically possible. The importance from a geological standpoint is that uncertainty of the deterministic geometry in unconstrained directions can be assessed whilst maintaining geological concepts and other constraints in the model. It is expected that methods in this area will be further developed as the construction and hence investigation and modelling of the repository proceeds. For this development it is important that the DFN modellers together with the geologists decide the preferred approach to address uncertainty in unconstrained directions of the deterministically modelled geometry.

6.4.3 Structures based only on surface data

Deformation zones of SDM-Site were modelled using an extrapolation methodology based on extending the structure as deep as the corresponding length of the lineament (given that no other constraints were found such as boreholes or terminations against other zones). The actual extent at depth is often uncertain as reported by Stephens et al. (2015). This is especially appropriate for minor deformation zones which are likely to be closer to the limit of the critical length of 200 m equivalent circular radius.

To address this uncertainty, it is possible to utilize a similar semi-stochastic principle as exemplified in Figure 6-6. Constraints are formed by the length of the surface lineament, truncation against other structures, presence of observations with tunnels, ground surface, or boreholes as exemplified in Figure 6-4. Using semi-stochastic modelling, multiple realisations of the zone can be created sampling alternative sizes for the zone. Further away from the repository, where information from boreholes, tunnels and outcrops is absent, deformation zones will need to be modelled entirely stochastically.

As pointed out in Section 5.4.8, deterministic sheet joint extrapolation presents a specific situation because of their vertical dilation nature in contrast to deformation zones that originate from shear movements. Deterministically modelled sheet joint constraints are established using explicit rules, as exemplified in Figure 5-17. The uncertainty of the individual size of a sheet joint can be semi-stochastically simulated using a similar method, as described in Figure 6-5b and Figure 6-7, or by using a stochastic conditioning approach as described by Bym and Hermanson (2018).

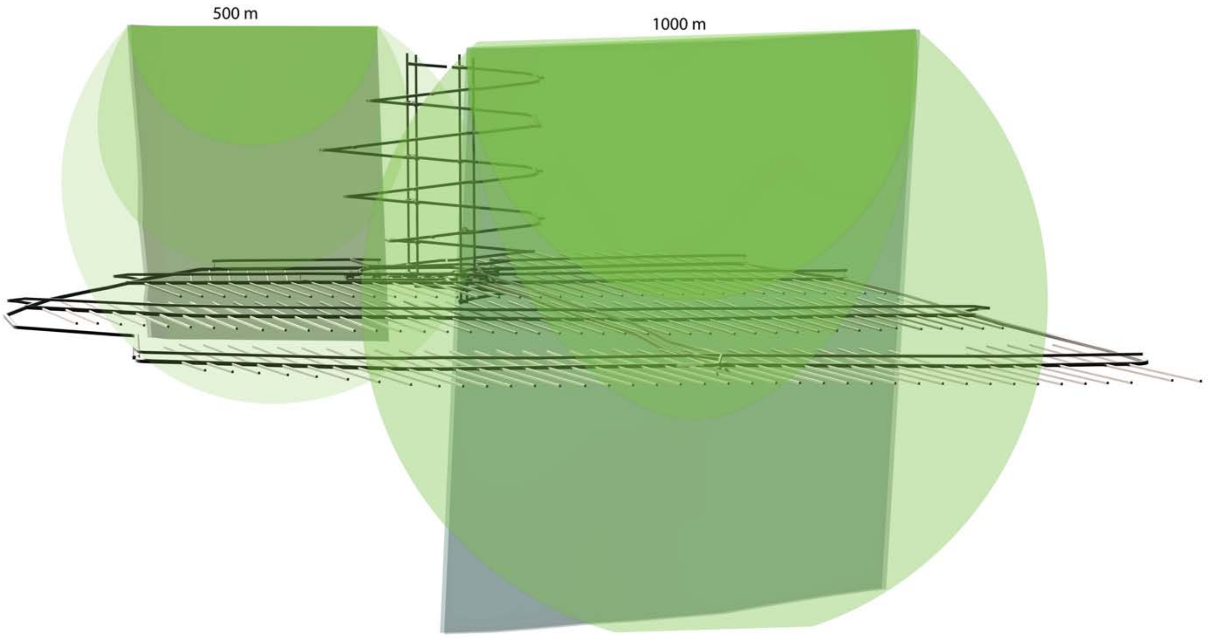


***Figure 6-6.** Schematic example of semi-stochastic modelling of a deformation zone that is based on a surface lineament. The size can be stochastic for each realisation while maintaining geologically defined constraints (the length of the surface lineament and any observations in tunnels or boreholes at depth).*

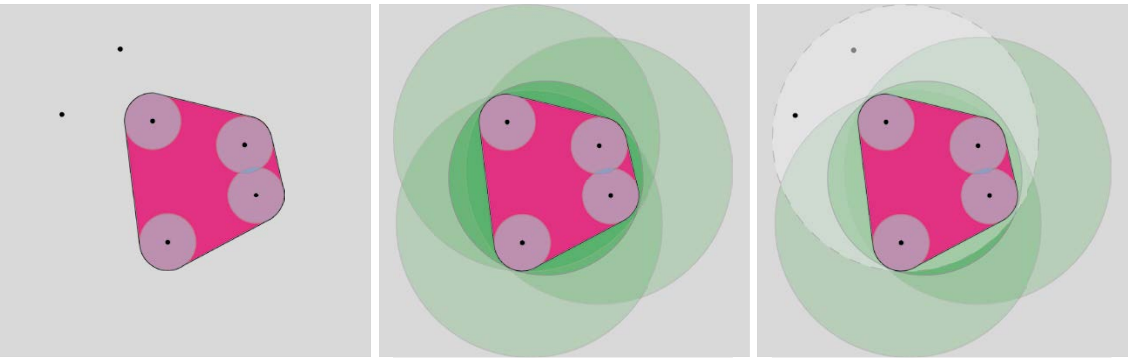


Figure 6-7. Schematic example of semi-stochastic modelling of a sheet joint that is based on several borehole intersections (explained in Figure 5-17). The deterministically modelled sheet joint (red) extends 1/3 of the maximum distance between observation points. In semi-stochastic DFN modelling both the size and centre of the structure will be determined stochastically, as indicated by three (green) possible disc shaped fractures. Constraints are given by other nearby boreholes that are not showing any presence of a sheet joint.

6.4.4 Attributes to find unconstrained deterministic structures

Any semi-stochastic approach will require that all deterministically modelled structures are reviewed before deciding how uncertainties in unconstrained geometries are best handled. Depending on their individual geological constraints, it will be possible to identify which deterministic geometries that are unconstrained in one or more directions (see Figure 6-4). Further to this, the naming convention for deterministic structures can be used to initially sort the three types of structural objects: surface based SDM-Site, underground derived, and sheet joints, as explained in Section 5.2.2. Each object contains information on all confirmed intersections with the surface, boreholes or tunnels as well as modelled geometrical constraints to other objects. Also, the confidence level in extrapolation (explained in Section 6.1.4) is a key attribute that explains how well a structure is constrained in strike and dip direction. Low and medium confidence in either direction indicates that the structure could be a candidate to be addressed through semi-stochastic modelling. High confidence indicates that the interpretation of the geometrical extent is well defined and can be used as is in downstream modelling.

6.5 Verification of modelled objects and alternative models

Assessment of validity of the deterministically modelled objects and the underlying concepts is an essential component of the modelling work. This should be carried out on a prediction-outcome basis, by comparison with data, interpretations or preliminary models which were never used in the modelling process. Independent tests of validity should include one or more of the following strategies to provide feedback to improve new interpretations:

- Complementary hydrological and geophysical surveys.
- Additional verification by boreholes that aim to intersect a modelled object. A GSHI is then carried out and predicted geometries and properties of the modelled object are compared to these results.
- Comparing GSHI from the pilot borehole with the STI for the corresponding tunnel. Although these data are acquired from methods covering two different scales, modelled structural intercepts from borehole data can be compared with interpreted intercepts in the STI.
- Comparisons between predicted geometries/properties of the modelled object and interpretations provided using additional information from geophysical or hydrogeological investigations.
- Comparing observed fracture data in a new borehole with the assembled fracture statistics from investigations over a larger volume (i.e. in that facility part) using DFN (see Selroos et al. 2022).
- Alternative models using stochastic DFN to evaluate uncertainty in the modelled deterministic objects. Such models can include other representations of deformation zones (alternative spatial extent, stochastic representations of internal geometry or variations along the zones (see Selroos et al. 2022).

Results from such exercises are used to improve interpretations and the deterministic geological models. Each verification aims to identify discrepancies from observations, interpretations, and modelled geometries, including conceptual assumptions. Depending on the outcome, assumptions, concepts, interpretations, or modelled geometry may need to be updated. Discrepancies should be reported together with any changes or adjustments that are introduced.

The strategy of having one or more verification boreholes was satisfactorily used throughout the preceding site descriptive modelling, both for verifications of predicted geometries and to reveal the nature of deformation zones solely based on lineaments and seismic reflectors. A good example is the cored borehole KFM08D, where the results from the SHI confirmed both domain boundaries and the existence of all deformation zones predicted during model stage 2.2 (see Figure 6-8). It thereby permitted an upgrade to a higher level of confidence in their existence.

The use of new boreholes to verify the existence of predicted structures is strongly recommended as an integrated part of the routine investigation during the construction of the repository, especially in deposition areas where the layout allows for an initial dispersed grid of pilot boreholes as a basis for predictions.

Another approach is to assess the overall confidence of the modelled objects based on initial data, with modelled objects based on more comprehensive data acquired as excavations (and investigations) proceeds. This approach is recommended to be carried out after completing a tunnel section, to quantify changes in the interpretation such that learnings can be carried on to the next excavation area.

A third supportive approach is an assessment of alternative object geometries with support from supplementary geophysical and/or hydrogeological interpretations. This can support adjustments to the relative confidence levels, but is limited as it is only based on indirect methods.

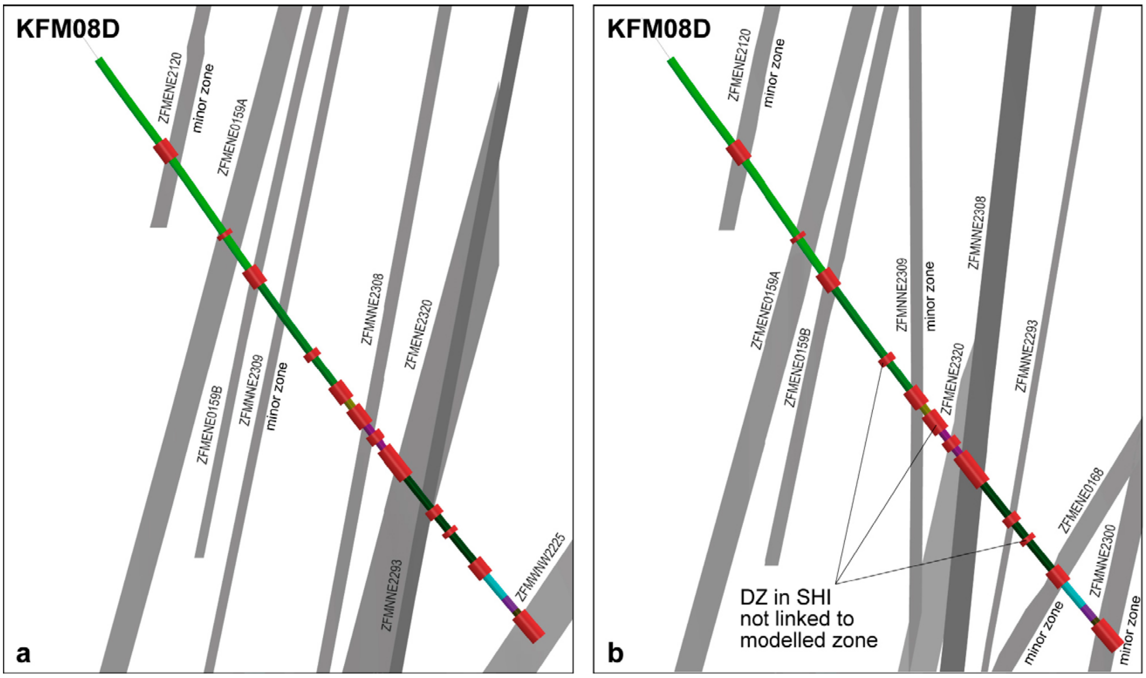


__Figure 6-8.__ Prediction-outcome test for deformation zones along borehole KFM08D. a) Modelled deformation zones stage 2.2 (ZFM), including minor zones, compared with the twelve possible deformation zones in the single-hole interpretation (red cylinders). b) Modification of zones necessary to satisfactorily match the single-hole interpretation. From Stephens et al. (2008).

Remaining issues to be continually evaluated are, amongst others:

- The conceptual understanding of the site, e.g. by new kinematic data of the brittle deformation.
- The geological evaluation of structures to support classification of critical structures.

Further to this, Munier et al. (2003) expressed that although the lack of knowledge may be expressed in terms of information density, this approach tends to focus on “hard” information such as data from boreholes, seismic profiles, etc, whereas “soft” information such as the conceptual understanding of a process and empirical experience tend to gain lesser focus. Since a considerable amount of information that forms the cornerstones of 3D modelling is processed or refined from primary data it is important to “overlay” each interpretation with a different source of information. A regional scale map of tectonic structures or stress maps can be used to gain further insight into how the object was once created and how the geological evolution story can be reconstructed. A large part of the geological understanding depends on the ability to explain historical events that have happened millions and even billions of years ago at much different physical conditions than today.

The process understanding, or conceptual model, involves progressive improvements of local detailed knowledge in combination with the application of the large-scale geological understanding of the site. The conceptual understanding of a site should be progressively tested during the construction of the repository. Simple concepts such as dominant orientations or truncations of certain structures against others can be used in making assumptions on how the rock mass is constituted beyond the tunnel front (or tunnel periphery), from information gathered only from pilot boreholes or in the interpretation of geophysical data. The conceptual understanding of a site will be tested progressively during the construction of the repository.

The underlying geological concepts and understanding of the geological development of the rock mass improve the ability to make qualified and well underpinned interpretations. However, a pre-conceived concept may also lead to erroneous or misleading interpretations. In addition to having a conceptual model of how the geology “worked”, it is important to also use alternative models to test other assumptions. Alternative models cover both the aspect of geometric representations as well as descriptions (such as DFN models or parameter values) within the same geometric framework. Alternative concepts and models also provide multiple options and interpretations that can be tested against downstream discipline models (such as hydrogeology, transport and rock mechanics) for objective guidance of a ”best case” interpretation.

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Appendix 1

Summary of the method descriptions for geological borehole and tunnel mapping

This appendix presents condensed versions of the method descriptions for geological borehole and tunnel mapping respectively, which are expected to provide the majority of the required data for the geological modelling during the construction and operation of the final repository. A summary of other available methods is presented in Table 3-1 of the main report. Also, in addition to these methods, there are a number of geophysical and geological methods carried out from the air and ground surface during the preceding site investigations.

SKB MD 143.006

Borehole mapping

Boremap is a digital system developed by SKB for geological logging of boreholes, which integrates traditional core logging with information from an optical image of the borehole walls (SKB MD 222.006). Whereas the drill core provides most of the geological details, an oriented borehole image reveals geometric data in terms of orientation and location for the geological objects. Thus, the borehole image is the preferred method for defining structural orientations. Additional support to the geological mapping can be provided by geophysical borehole logging (SKB MD221.002 and SKB MD 221.003).

The Boremap system consists of three independent software components: where Boremap is the core of the system, Access is the database engine and WellCAD is the tool for graphical data visualization. Boremap requires synchronization with SKB's site characterization database, SICADA, to access metadata for setup, borehole parameters (e.g. deviation measurements) and storage of mapping data. The local Access database is hence, used only as working storage between synchronizations with SICADA. A system overview is presented in Figure A1-1. From SICADA, the logging data can be extracted to SKB's 3D modelling tool, RVS (Rock Visualization System).

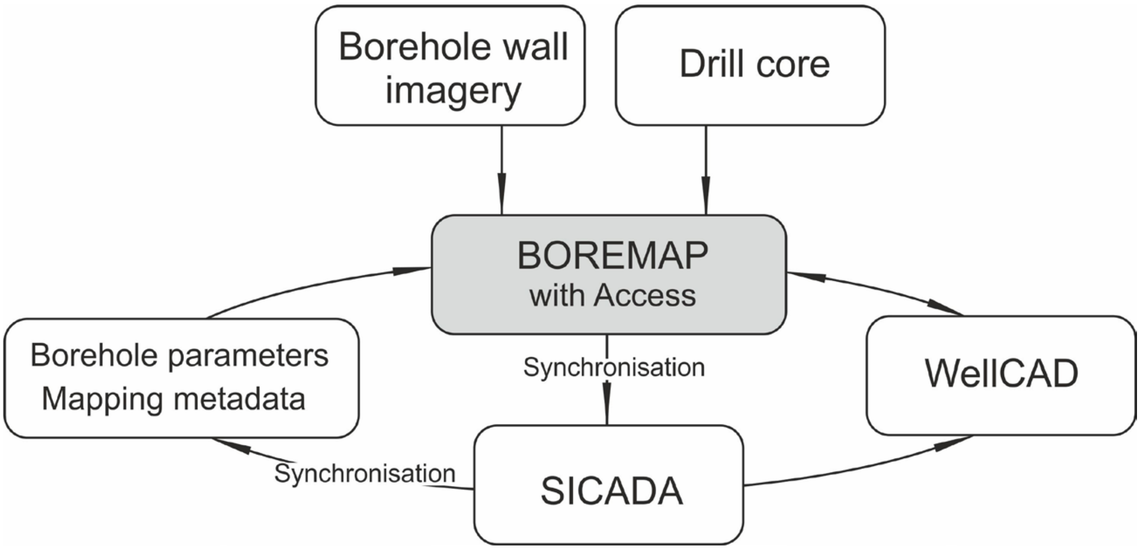

Figure A1-1. Illustration showing the components of the Boremap system.

As the primary focus for the development and improvement of Boremap, the mapping of fractures along boreholes deserves special attention. All fractures inferred to be *natural* shall be registered during the mapping. Natural fractures within the rock mass are separated into open, partly open and sealed, in accordance with the nomenclature of SKB presented by Stråhle (2001). During the borehole mapping, however, the first step is to register a natural fracture as broken or unbroken, depending on whether it splits the drill core or not. The next step is to determine whether the fracture has an aperture or not, based on information from *both* the drill core and the optical borehole image. Based on this, the fracture is classified as open, partly open or sealed by SICADA, according to the criteria presented in Figure A1-2 and Table A1-1. Thus, a broken fracture in the drill core can be classified as either open or sealed, depending on the assigned value for aperture, whereas an unbroken fracture can be classified as sealed or, if the fracture filling material has distinguishable voids or channels, as partly open.

The fracture width (thickness of the fracture mineral) is measured in the borehole image at the fracture inflection point (i.e. amplitude = 0). If no image is available, the fracture width is measured from the drill core. The minimum measurable width is 1 mm. Fractures that are thinner are assigned a standard width of 0.5 mm (because a numerical value must be specified in Boremap).

In SICADA, the mapping of individual fractures is presented in the table ***p_fract_core*** (Table A1-2).

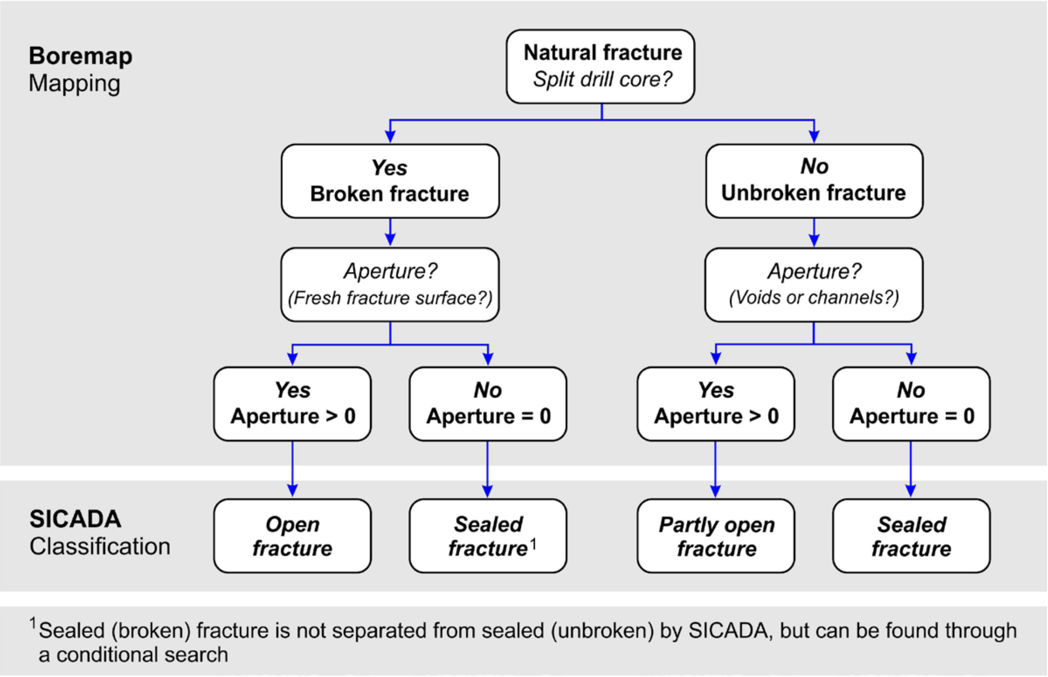

Figure A1-2. *Flowchart showing the criteria for classification of individual fractures registered by Boremap.*

Table A1-1. Nomenclature and criteria for individual fractures in SICADA.

Sealed (unbroken) fracture

Natural fracture filled by consolidated fracture minerals, such as quartz, epidote or calcite. The fracture does not split the drill core.

Fract_mapped = Unbroken Aperture = 0 Fract_interpret = Sealed

Sealed (broken) fracture

The subgroup is not separated from sealed (unbroken) by SICADA but can be found through a conditional search. These natural fractures are inferred to be sealed in the rock mass but have been broken during the drilling or the subsequent handling and do hence split the drill core. A sealed (broken) fracture is defined by (1) an apertureless fit between the two drill core parts and (2) fresh (lack of weathering) fracture surfaces.

Fract_mapped = Broken Aperture = 0 Fract_interpret = Sealed

Open fracture

Natural fracture filled by fluids or nonconsolidated material. The fracture split the drill core and is inferred to have aperture. It can be difficult to determine whether a fracture that split the drill core has aperture (i.e. has been open within the rock mass) or it broke up during the drilling process. If uncertainty prevails, the fracture is assigned an aperture, and consequently classified as open by SICADA. All such fractures shall be assigned a confidence level, according to the following criteria:

- Certain Aperture visible in the borehole image (aperture is measurable, varies 1–x mm)
- Probable Drill core parts do not fit perfectly together (aperture = 0.5 mm)
- Possible Weathered fracture surfaces (aperture = 0.5)

Note that the fracture confidence concept only is valid for open fractures; it only indicates how confident the mapping geologist is that the aperture really exists and has no connection to any other fracture properties.

Fract_mapped = Broken Aperture > 0 Fract_interpret = Open

Partly open fracture

Natural fracture that not split the drill core but have open voids or channels. The aperture is determined based on the borehole image if available, otherwise on the drill core. The minimum measurable aperture is 1 mm, fractures with smaller voids are assigned aperture = 0.5 mm (because numerical value must be specified in Boremap).

The number of partly open fractures is an absolute minimum, as the open (broken) fracture group also includes fractures with voids and channels. However, a separation of these fractures during the mapping has not been considered, due to the risk of overinterpretation.

Fract_mapped = Unroken Aperture > 0 Fract_interpret = Partly open

Artificial fracture

By definition only distinguishable in the drill core and shows no fracture minerals or alterations. In practice, artificial fractures (breaks) are the result of external force against the drill core, for example through the drilling or when the drill core must be split to fit in the core box. Artificial fractures are mapped only on special request. Artificial fractures resulting of handling are indicated by an ”F” in the drill core boxes. A special case is if the drill core is split along a natural fracture, then it is marked with “F” and should be mapped as an unbroken fracture with the aperture = 0.

Table A1-2. Detail from parameter table p_fract_core in SICADA.

IDCODE	VARCODE	ADJUSTEDSECUP	FRACT_MAPPED	FRACT_INTERPRET	APERTURE	CONFIDENCE_CODE	CONFIDENCE
KFM01A	2	102.67	Broken	Sealed	0.0	1	Certain
KFM01A	2	103.06	Broken	Open	0.5	3	Possible
KFM01A	3	106.13	Unbroken	Sealed	0.0	1	Certain
KFM01A	3	122.71	Unbroken	Partly open	1.0	1	Certain

Highly fractured sections of the drill core where individual fractures cannot be mapped are divided into two main categories: (1) sealed fracture network and (2) crush. This happens where the drill core can only be reconstructed with difficulty or where the distance between the fractures is less than about 5 cm. In contrast to individually mapped fractures, these sections are classified and registered directly by the mapping geologist. The decision whether it is a crush or a sealed fracture network is made based on the cohesion of the drill core.

Sealed fracture networks are assigned an average fracture distance (i.e. piece length) and, if possible, two main fracture orientations (*strike3/dip3* and *strike 4/dip4* in SICADA) based on the borehole image. If the image is missing, the properties are based on drill core observations. Fractures with markedly different properties within the sealed fracture network (e.g. orientation or fracture minerals) are mapped as individual fractures.

Crush is, by definition, distinguished in the drill core and not in the borehole image. The interval identified as crush is assigned an average piece length and, if possible, two main fracture orientations (*strike3/dip3* and *strike 4/dip4* in SICADA).

Orientation and piece length are determined based on the borehole image. If the image is missing, the properties are based on drill core observations.

In SICADA, the mapping of sealed fracture networks and crush is presented in the tables *p_fract_sealed_nw* and *p_fract_crush*, respectively (Table A1-3).

Table A1-3. Detail from parameter table p_fract_sealed_nw and p_fract_crush in SICADA. Varcode 4 = crush and varcode 32 = sealed fracture network. Strike/Dip is the orientation of adjustedsecup, strike2/dip2 is the orientation of adjustedseclow, whereas strike3/dip3 and strike 4/dip4 are the two main fracture orientations in the interval of the crush or sealed network. Adjustedsecup and adjustedseclow refer to the start and stop of the section defined as crush or sealed fracture network.

IDCODE	VARCODE	ADJUSTED-SECUP	ADJUSTED-SECLOW	STRIKE	DIP	STRIKE2	DIP2	STRIKE3	DIP3	STRIKE4	DIP4	PIECE_LENGTH
KFM13	4	13.91	13.97	177.0	31.2	45.9	9.4	33.5	11.8	57.3	10.7	7.0
KFM13	32	48.66	48.98	149.7	67.8	171.9	66.0	169.0	72.3	178.9	28.1	10.0

In addition to the tables for individually mapped fractures, or as mapped as assemblages, there are fracture frequency tables in SICADA, which combine the two types of fracture mappings. The relationship between the different mapping types and the tables is presented in Figure A1-3.

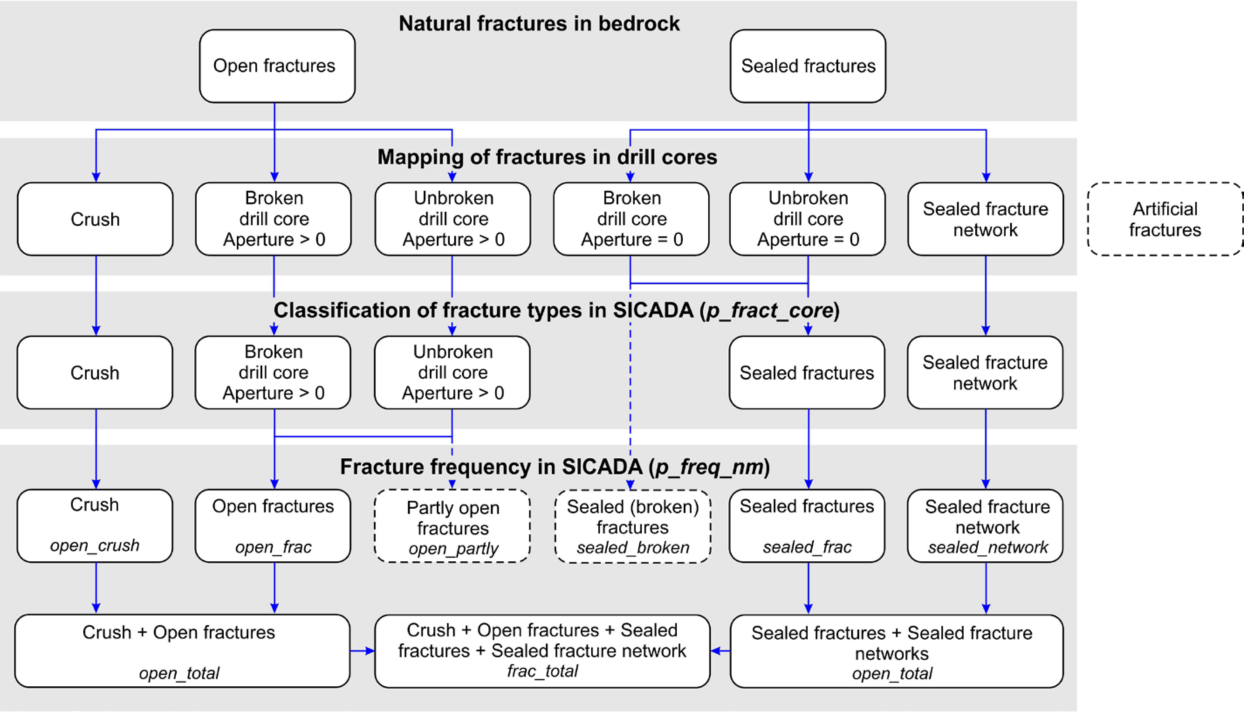

Figure A1-3. *Flowchart showing the relationship between natural fractures in the bedrock, the fracture mapping by Boremap and the presentation in SICADA.*

The fracture frequency is calculated for a number of different section lengths (1, 3, 4, 5, 10 and 30 m) based on the tables *p_fract_core*, *p_fract_sealed_nw* and *p_fract_crush*. The calculated parameter tables are denoted *p_freq_nm* (where n is step length). In order to obtain the fracture frequency with the unit m^{-1}, the number of fractures is divided by the length of the interval. Note that the length of the first and last interval may differ from the other intervals. Table A1-4 gives an example of an extract of *p_freq_1m*.

Table A1-4. Detail from parameter table p_freq_1m in SICADA. The open_partly column (i.e. interpreted as sealed with channels) contains only from the unbroken group with aperture > 0. Note that partly open fractures are also included in the statistics in open_frac column.

IDCODE	ADJUSTEDSECUP	ADJUSTEDSECLOW	BROKEN	UNBROKEN	OPEN_FRAC	OPEN_CRUSH	OPEN_TOTAL	OPEN_PARTLY	SEALED_FRAC	SEALED_NETWORK	SEALED_TOTAL	SEALED_BROKEN	FRAC_TOTAL
KFM01A	102.08	103.00	1	0	0	0	0	0	1	0	1	1	1
KFM01A	103.00	104.00	1	0	1	0	1	0	0	0	0	0	1
KFM01A	104.00	105.00	3	0	0	0	0	0	3	0	3	3	3
KFM01A	105.00	106.00	7	0	6	0	6	0	1	0	1	0	7
KFM01A	106.00	107.00	0	1	0	0	0	0	1	0	1	1	1
KFM01A	107.00	108.00	4	0	3	0	3	0	1	0	1	0	4
KFM01A	108.00	109.00	3	1	3	0	3	0	1	0	1	0	4
KFM01A	109.00	110.00	1	0	1	0	1	0	0	0	0	0	1
KFM01A	110.00	111.00	4	0	4	0	4	0	0	0	0	0	4
KFM01A	111.00	112.00	4	0	4	0	4	0	0	0	0	0	4
KFM01A	112.00	113.00	2	1	2	0	2	0	1	0	1	0	3
KFM01A	113.00	114.00	6	0	5	0	5	0	2	0	2	1	7
KFM01A	114.00	115.00	5	0	5	0	5	0	0	0	0	0	5
KFM01A	115.00	116.00	6	0	5	0	5	0	1	0	1	1	6
KFM01A	116.00	117.00	3	0	3	0	3	0	0	0	0	0	3
KFM01A	117.00	118.00	0	0	0	0	0	0	0	0	0	0	0
KFM01A	118.00	119.00	4	0	1	0	1	0	3	0	3	3	4

SKB MD 150.011

Mapping of rock surfaces

The Rock Characterization System (RoCS) is a digital system developed by SKB for geological mapping of underground openings (tunnels, shafts and niches, etc) based on photogrammetric 3D models (SKB MD 150.010). The system is currently developed to allow usage also for outcrops and tunnel portals and replaces the SKB's methods for bedrock mapping (SKB MD 132.001) and detailed fracture mapping (SKB MD 132.003), which are no longer in use. The method is based on digitizing the spatial extent of various geological objects on the photogrammetric 3D model. Geological details, such as fracture mineralogy and surface properties, which cannot be distinguished in the images, still require physical mapping of the rock surface.

RoCS consists of two independent software components: where RoCS is the core of the system and Access is the database engine. Similar to Boremap, the current RoCS version requires synchronization with SKB's site characterization database, SICADA, to access metadata for setup and storage of mapping data. The local Access database is hence, used only as working storage between synchronizations with SICADA. A system overview is presented in Figure A1-4. From SICADA, the mapping data can be extracted to SKB's 3D modelling tool, RVS (Rock Visualization System).

All fractures inferred to be *natural* shall be registered during the mapping. In contrast to the borehole mapping, there are no attempts to distinguish between open, partly open and sealed during the mapping of rock surfaces. Blast or stress relief induced fractures (i.e. artificial factures) are only registered while mapping deposition holes, but can be mapped in other parts on special request.

Fractures mapped in RoCS are registered as trace lines (*rocs_fracture*).

A lower cut-off length for fracture traces is applied to all mappings. The default cut-off value for detailed mapping is 1 m and for overview mapping 3 m, with the possibility of changing it for selective investigations where a higher resolution is requested by DFN modelling. Such specific investigations could, by request, involve selective tunnel sections or investigations of specified deformation zones. The cut-off trace lengths shall be constant throughout the routine mapping activities to minimise data gathering biases.

Fracture width and aperture is measured on the rock surface and refer to maximum representative width/aperture. Associated water leakage and fractures with highly variable aperture are noted by the field names *water_found* and *channeling*, respectively. The minimum measurable width is 1 mm. Fractures that are thinner are assigned a standard width of 0.5 mm (because numerical value must be specified in RoCS).

Areas of intense ductile, brittle-ductile and brittle deformation are mapped as areas of intense deformation with specification of structural character, structure type and possible inflow. Main fracture sets within an area of intense deformation are registered by the parameter *rocs_fracture_set*. Each set is represented geometrically by a *single* fracture trace line and provides information on spacing and number of fractures.

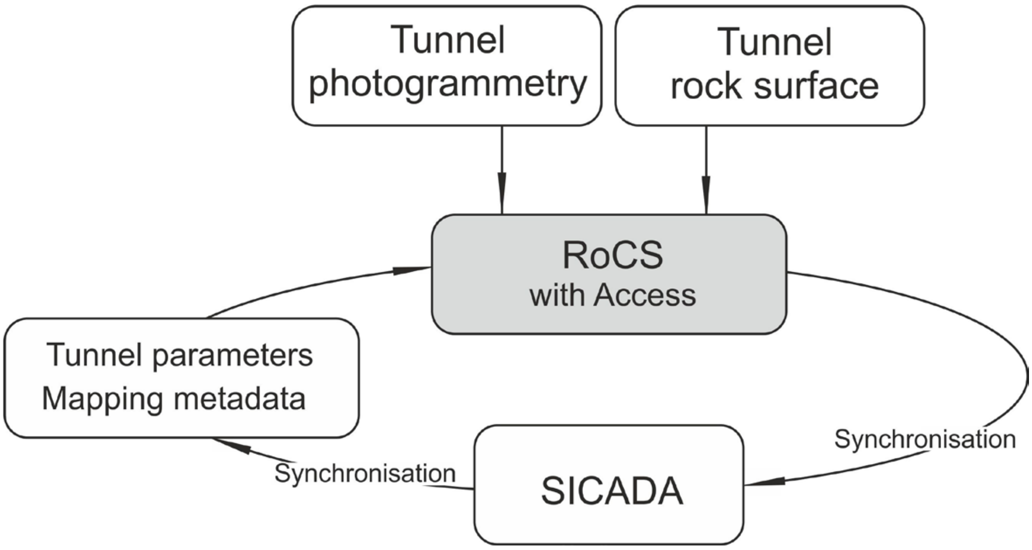

Figure A1-4. *Illustration showing the components of RoCS.*

Appendix 2

Geoscientific single-hole interpretation (GSHI)

Methodology for integrated synthesis of geological data from boreholes with support from hydrogeological and geophysical data

A2.1 Background

The methodology for geological single-hole interpretation (SHI) was originally introduced for use in the site descriptive modelling at Forsmark and Laxemar, as an intermediate step between basic assembly of borehole data and the subsequent 3D deterministic modelling, by providing an integrated synthesis of the geological and geophysical information in a given borehole. The objective of the methodology was to identify, describe and quantify both rock units (RU) and possible deformation zones, (referred to as PDZ) along individual boreholes.

Since the last released version of the SHI method description, established in 2006 (SKB MD 810.003[7]), the application has been updated in several aspects. Most important update was the introduction of the "simplified single-hole interpretation" which, in the absence of useful logging data, was applied initially to drill cores from the construction of the SFR (Petersson et al. 2011) and later also to older drill cores from the Äspö Hard Rock Laboratory (Petersson et al. 2017). Another addition was to include hydrogeological indications in the designation and characterization of PDZs (e.g. Petersson et al. 2010, 2011).

A2.2 Objective and scope

The updated methodology presented herein includes the multidisciplinary approach used in earlier stages and are named Geoscientific Single Hole Interpretation (GSHI). Two types of GSHI are planned:

- Overview GSHI – used as the principal input to an update of the geotechnical baseline report in support of engineering-related decisions.
- Detailed GSHI – used as the key link between primary data and the modelling work, by way of a multidisciplinary synthesis of geological data with support from geophysical and hydrogeological information in a borehole.

The overview GSHI has been developed from the simplified SHI to be the principal input to an update of the geotechnical baseline report in support of engineering-related decisions. An early version of the methodology for the overview GSHI was tested on two pilot boreholes (KA3011A01 and KA3065A01) at Äspö Hard Rock Laboratory (Äspö HRL) providing valuable input to finalizing this document.

The methodology for the detailed GSHI comprises primarily the following changes to previously used methods:

- Change in nomenclature – possible deformation zone (PDZ) is now changed to borehole deformation zone (BDZ).
- Increased focus on multidisciplinary integration by introduction of hydrogeological data in the interpretation process. A conductive fracture identification (e.g. Teurneau et al. 2008, Öhman et al. 2010) is now included as a basis for the interpretation.
- An initial step of disciplinary-specific evaluation where geologists, geophysicists and hydrogeologists work separately to generate a basis for the subsequent step of multidisciplinary interpretation.

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[7] SKB MD 810.003 Metodbeskrivning för geologisk enhålstolkning, version 3.0. Stephens et al. 2006. Internal document.

- Efforts to increase the detail of the interpretation by addressing also smaller sized RU and BDZ. This has been tried by Fox and Hermanson (2006) through the "extended single-hole interpretation", with the purpose to identify possible additional deformation zones below the resolution threshold applied during the first stage of the site investigation programme.
- The compilation of RU and BDZ property tables, which includes geological, hydrogeological and geophysical criteria for identification, geometric details, quantified properties and confidence in interpretation.
- Based on the rock type character in Forsmark, it was decided to exclude geophysics in the process of RU identification.

The order of execution of the overview and detailed GSHI relative to other activities within the investigation, interpretation and modelling sequence is illustrated in Figure A2-1. Even if no hydrogeochemical and rock mechanical data are considered in the GSHI interpretation, it is valuable for the subsequent integration work these disciplines also participate in the GSHI to provide common understanding of the borehole.

A2.3 Applicability

The implementation of the methodology for the detailed and the overview GSHI during construction and operation of the final repository will be restricted to cored boreholes. All available investigation data, such as borehole geophysics and hydraulic logs can be used in support of the interpretation, but do not constitute prerequisites for executing the GSHI.

The methodology does not include the use of percussion-drilled boreholes. Details on the application of SHI to percussion-drilled boreholes are given by Munier et al. (2003) and in Appendix 6 of SKB MD 810.003.

Notably, a GSHI is always carried out independently for each borehole.

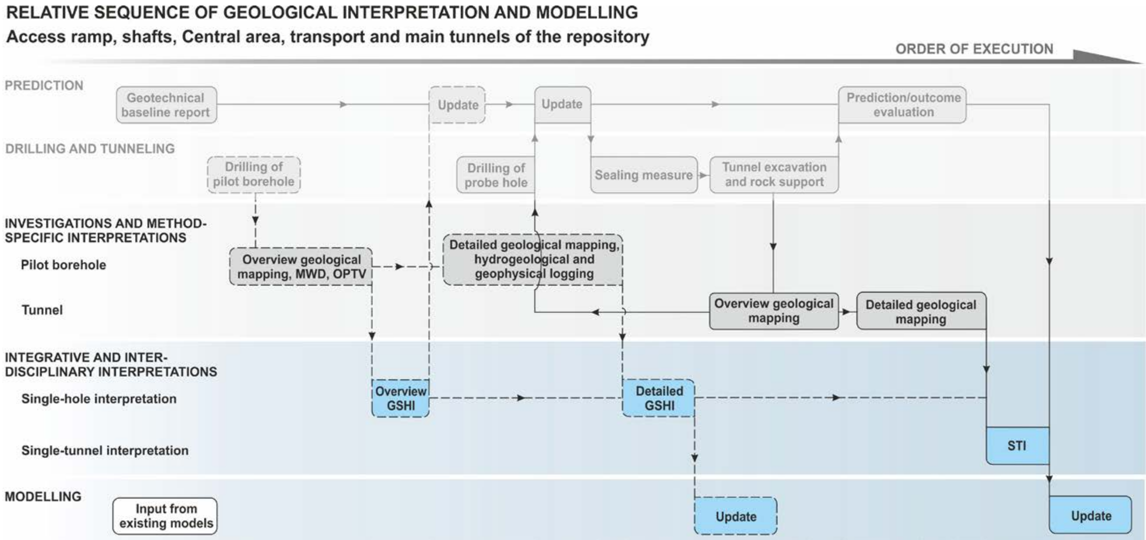

Figure A2-1. *The order of execution of the overview and detailed GSHI relative to other activities within the investigation, interpretation, and modelling sequence. Modelling is included to illustrate when action is recommended. The flow chart does not describe decisions needed to proceed with each step.*

A2.4 General work procedure

Overview GSHI

The overview GSHI is intended to support engineering-related decisions (cf Figure A2-1). To carry out the overview GSHI it is not necessary to have access to the full spectrum of borehole data. Instead, the primary data for the methodology is confined to ocular drill-core examination, geological overview mapping (activity type GE044 in SKB MD 143.006), along with water inflow measurements during the drilling. Thus, an overview GSHI can be accomplished within a few hours after the completion of the core drilling.

The focus of the overview GSHI is to identify brittle structures which have possible implications for the stability of, and water inflow to, the tunnel. To provide this information, the overview GSHI aims only at the identification of sections of increased brittle deformation, which are denoted borehole fracture zones (BFZ) to separate the nomenclature from the more comprehensive identification of deformation zones made in the detailed GSHI.

The working process of the overview GSHI can be separated into these steps:

1. Graphical compilation of logs showing parameters of the geological overview mapping and hydraulic data from the drilling.
2. An initial geological interpretation of sections with increased brittle deformation supported by hydrogeological data from the drilling.
3. Ocular drill-core inspection for follow-up and possible reconsideration of the initial interpretation (step 2).
4. Definition and description of identified BFZ intervals.

Orientation data for inferred zones are added, if OPTV is available; alternatively, a crude estimate can be made based on the α-angle (between structure plane and borehole axis). An overview flowchart of the sub-activities and products is presented in Figure A2-2.

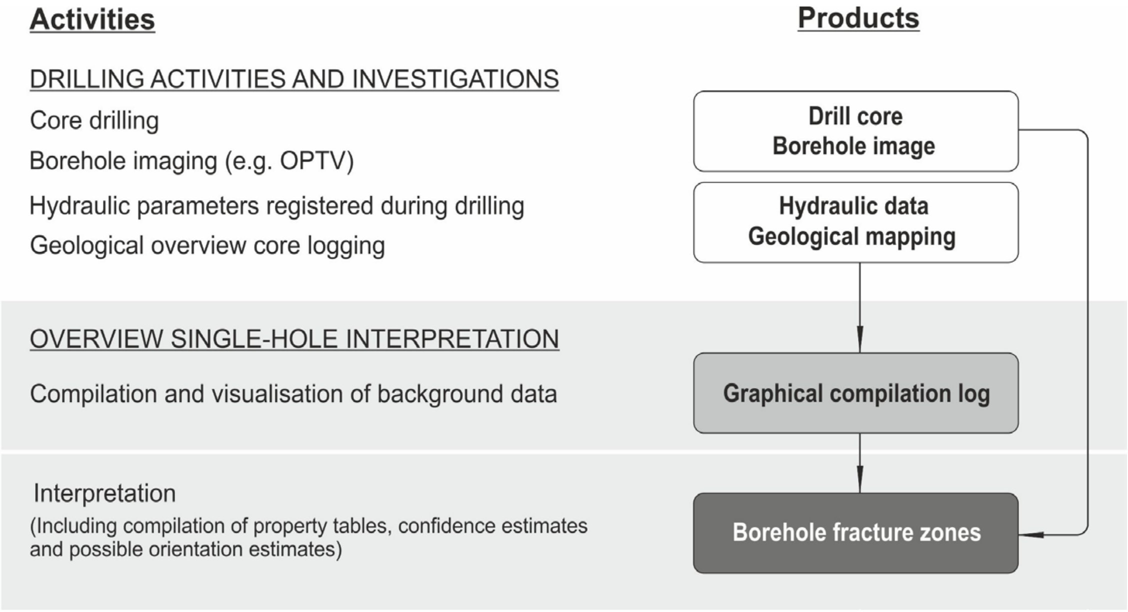

Figure A2-2. Overview flowchart showing the steps in the overview GSHI procedure for identification of borehole fracture zones (BFZ).

Detailed GSHI

The basic concept of the detailed GSHI is to simplify the observed geological complexity along a borehole to be represented by two entities; rock units (RD) and borehole deformation zones (BDZ). The borehole will be covered continuously by RDs whereas BDZs are identified where adequate data exists. This simplification aims to support later 3D modelling activities focused on identifying critical structures and volumes (cf Posiva SKB 2017). Thus, these two entities are the essential building blocks along borehole paths for correlation of geological objects between boreholes and tunnels. A fundamental aspect is that the entities identified and described by the GSHI remain fixed regardless of subsequent 3D geometric modelling activities. This independence from subsequent modelling activities or (hydraulic) time-dependent data or interpretations is made to retain full traceability to the original GSHI interpretation. Thus, the naming of individual GSHI entities, should be free from all references to any 3D modelled objects. Also, the detailed GSHI can be carried out independently to whether or not an overview GSHI exists for the borehole.

During the detailed GSHI, the identification of BDZs and RUs follows a process that involves the following steps:

1. Graphical compilation of logs showing parameters of the detailed geological, geophysical, and hydrogeological investigations of a single borehole.
2. Discipline-specific data evaluation to establish a joint platform for interpretation.
3. A multidisciplinary interpretation using graphical compilation logs to identify BDZs and RUs.
4. Ocular drill-core inspection for follow-up and possible reconsideration of the BDZ and RU interpretations.
5. Kinematic analysis of high confidence BDZs to support identification of potential critical structures.
6. Description of identified BDZ and RU intervals.

For step one, it is required that available borehole data are much more comprehensive than during the overview GSHI and the same applies to the compilation of logs. In the second step, all disciplines prepare their own interpretation so that the multidisciplinary interpretation (steps three to six) can be carried out and reported efficiently.

The third and fourth step aims to identify and characterize identified BDZs and RUs along the borehole. The fifth step of kinematic analysis is only carried out on high confidence BDZs to evaluate possible slip-directions as support to the 3D modelling. For practical reasons this step is carried out at a later stage as it may require more time and possibly also other types of expertise.

In step six the interpreted length intervals of RUs and BDZs is reported with a description of its properties, which includes an estimate of confidence in the interpretation of each defined interval. It is good practice that for BDZs identified with high confidence to also conceptualize the internal build-up of its core and damage zone. An overview flowchart of the sub-activities and products of the detailed GSHI is presented in Figure A2-3.

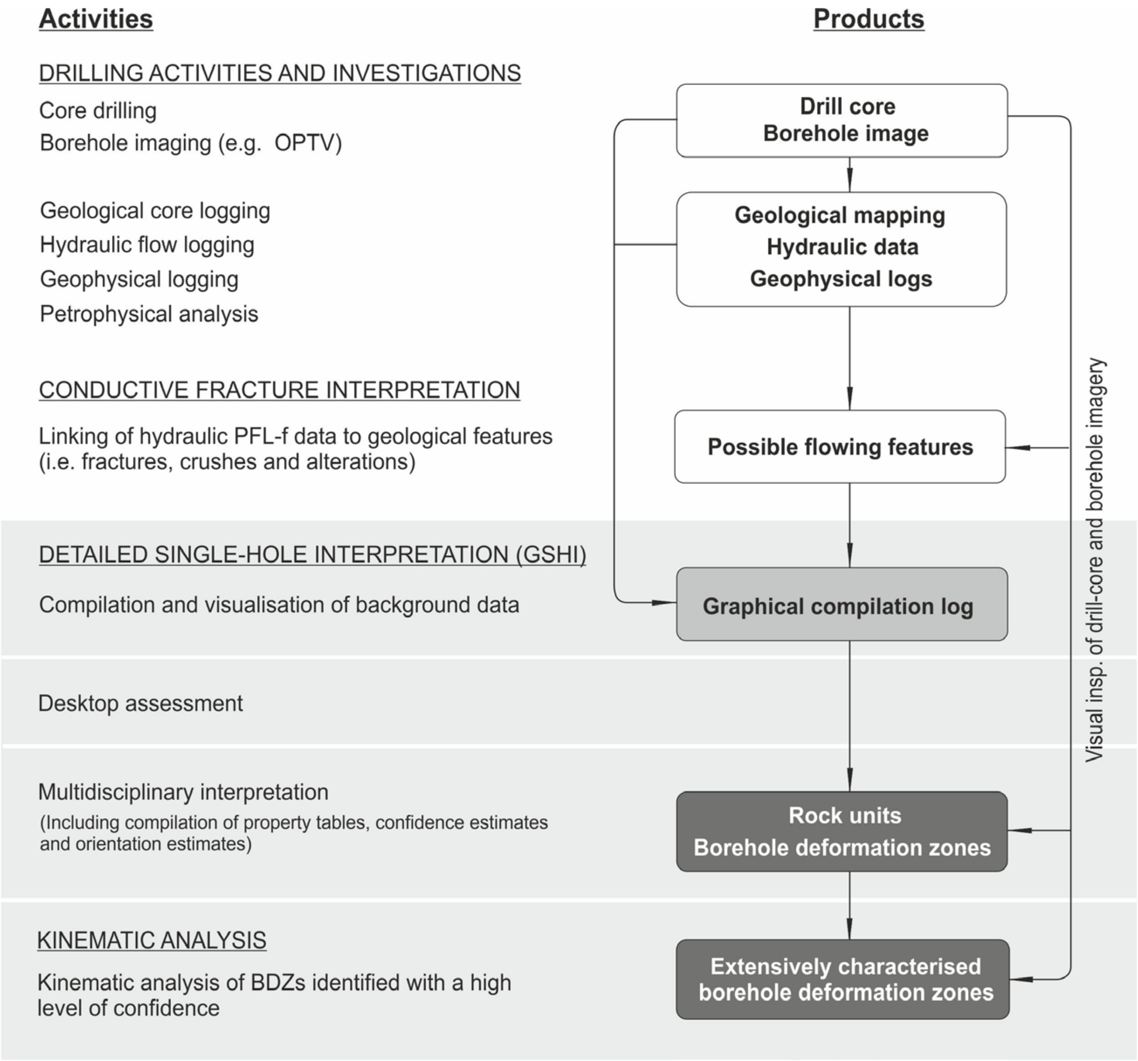

Figure A2-3. *Overview flowchart showing the steps in the detailed GSHI procedure for the identification of rock units and borehole deformation zones.*

A2.5 Compilation and visualisation of borehole data

Data and interpretations used in the GSHI analysis are summarised in Table A2-1, along with identification of the applicable SKB method descriptions. The complete range of data and interpretations available to carry out the GSHI may differ depending on the purpose of the borehole.

Available parameters in Table A2-1 are compiled graphically, as logs or series of logs by the use of a visualisation tool. Given the large number of parameters available, only those of relevance for the *identification* of BDZs and the *division* into rock units should be visualized. For example, this do not require detailed parameters, such as fracture mineralogy. See example for a suitable selection of fracture parameters that can be used for the analysis of the detailed GSHI in Figure A2-4 as well as the more rudimentary information needed for the overview GSHI in Figure A2-5.

The GSHI interpretation is dependent on the plotted resolution of data; therefore, it is strongly recommended that the plotted resolution will be standardised to a fixed length scale of 1:200. A length scale of 1:500 was used for SHIs performed during the site descriptive modelling at Forsmark and Laxemar. A higher resolution is recommended for the sub-surface investigations considering the shorter length of the planned underground pilot boreholes.

Table A2-1. Input to the overview and detailed geoscientific single-hole interpretation, along with the corresponding SKB method descriptions.

Overview GSHI:	
Drill core	SKB MD 620.003, SKB MD 143.007
Geological overview logging	SKB MD 143.006
OPTV borehole image (optional)	SKB MD 222.006
Registration of flush and return water parameters for underground core drilling	SKB MD 640.010
Detailed GSHI:	
Drill core	SKB MD 620.003, SKB MD 143.007
Detailed geological logging by Boremap	SKB MD 143.006
OPTV borehole image	SKB MD 222.030
Geophysical borehole logging (optional)[1]	SKB MD 221.002, SKB MB 221.003
Conductive fracture interpretation (optional)	e.g. Teurneau et al. 2008
Difference flow logging (optional)	SKB MD 341.013, SKB MD 341.021
Hydraulic single-hole tests (optional)	SKB MD 341.016

[1] Geophysical methods planned to be used by routine in pilot boreholes are specified in Lehtimäki T, Mattsson H, 2019. Metoder för geofysisk loggning i pilotborrhål. SKBdoc 1872469 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.) (Internal document.)

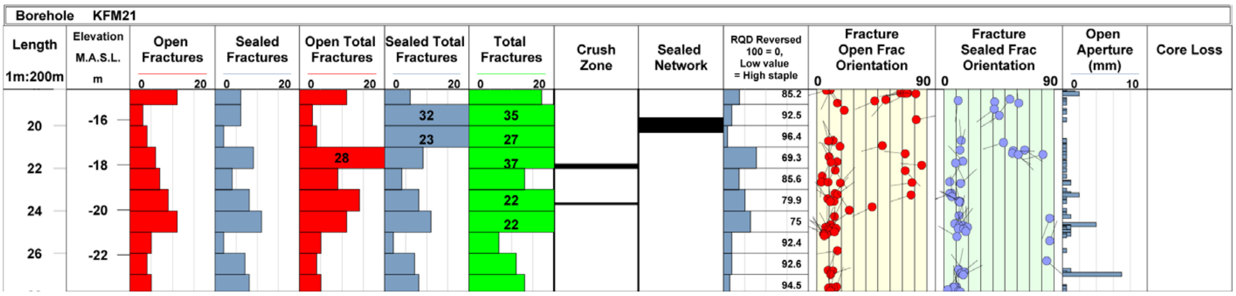

Figure A2-4. Example of a borehole log showing relevant fracture parameters to be used for a detailed GSHI. For readability, other useful parameter columns such as rock type, rock alteration, geophysics and hydrogeology are omitted in this example.

A2.6 Execution

Overview GSHI execution

The overview GSHI analysis starts with a joint multidisciplinary interpretation using the overview core logging and water inflow measurement during drilling, cf Figure A2-5. Intervals with BFZ are identified in the logs. Only structures of possible relevance for tunnel construction (i.e. to support engineering-related decisions) are considered. For BFZs there is no lower limit in borehole (section) length; even individual fractures may be included if they are judged to affect stability or show considerable hydraulic inflow. Characteristics judged to be of significance for identification of BFZs are listed in Table A2-2.

During ocular inspection of the drill core, identified intervals of BFZs are verified or adjusted. Some structures identified initially may be rejected, whereas other may be added.

Each BFZ should be briefly characterised according to the guidelines in Table A2-3. The result is also presented graphically, for example as a composite log, which displays the basis for the interpretation alongside the BFZ interval.

Table A2-2. Geologic and hydrogeological basis for identification of BFZs.

Parameter	Description
Broken fracture frequency	Anomalously high frequency of broken fractures (i.e. fractures that split the drill core) and/or the occurrence of crushed intervals
Hydrothermal alteration	Presence of rock alteration of such intensity and character that it may affect the mechanical properties of the affected rock
Fracture/Crush filling	Anomalously low fracture shear strength due to the presence of incohesive mineral filling (e.g. clay minerals or chlorite) and/or lack of surface roughness
Fracture/Crush orientation	Unfavourable orientations relative to the tunnel geometry (optional, requires borehole image)
Water inflows	Inflows of significance for estimation of sealing measures

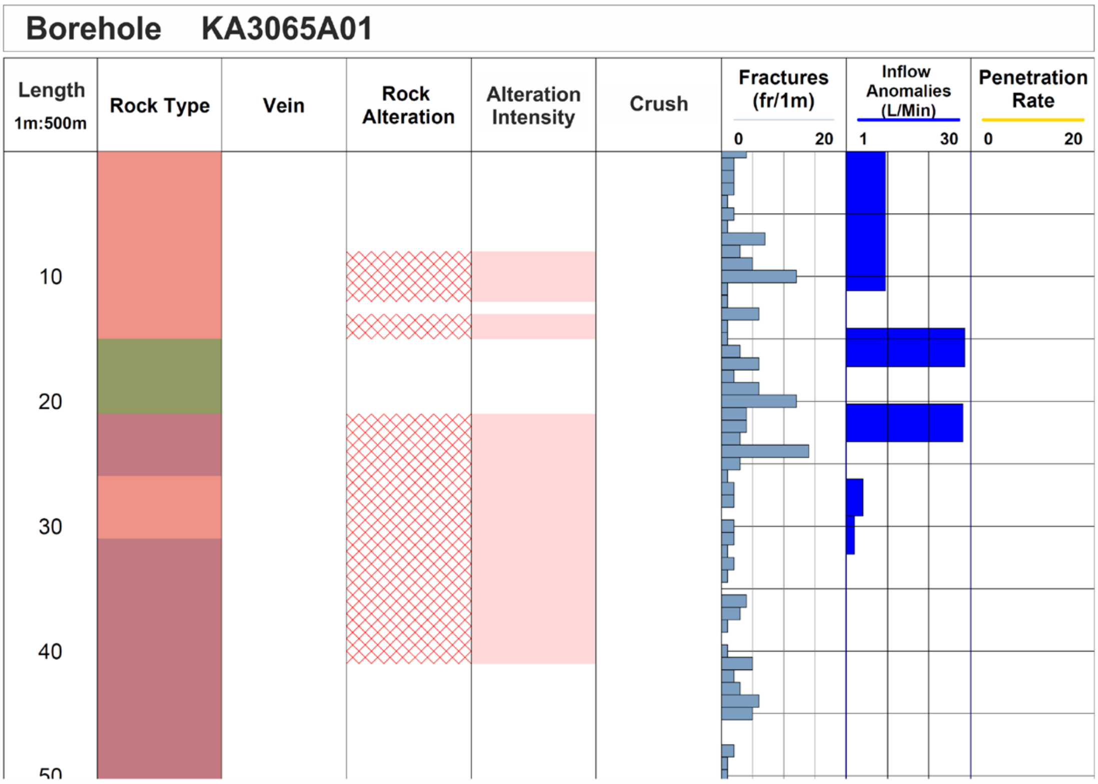

Figure A2-5. Example of relevant parameters for carrying out the overview GSHI.

Table A2-3. Suitable description for characterising BFZs identified during the overview GSHI.

Borehole fracture zone
– Borehole length
– Alteration
– Broken fracture frequency[1]
– RQD
– Fracture surface properties
– General fracture orientations[2]
– Inflow (borehole length and amount)
– Comments (criteria for identification)

[1] Fractures that split the drill core into pieces.

[2] If fracture orientations are available.

Detailed GSHI execution

The detailed GSHI analysis begins with an individual evaluation of data by each scientific discipline with focus on trends and anomalies to facilitate the next step where all disciplines meet for a joint interpretation.

In the joint interpretation, a compilation of relevant logs are used to identify BDZs and RUs along the borehole. Before a final decision on the existence and extent of BDZs and RUs along the borehole, the interpretation is verified by an ocular inspection of the drill-core. Modifications can include changes in the borehole section length of BDZs or readjustments of boundaries between RUs.

Sections of RUs are based on combining rock types with similar lithological, thermal and structural character. The minimum extent and true thickness of identified units are discussed in the main report (Section 4.3, 6.4 and 6.6). Briefly, for rock types with anomalously low thermal conductivity, the minimum true thickness of a RU is in the order of 1–2 m according to Lönnqvist[8].

Sections of identified BDZs are intended to capture deformation zones of such magnitude that they could exceed a diameter of 400 m (see Hökmark et al. 2019). Identification of BDZs is focused on indicators of shear movements and borehole sections of anomalous high fracture frequency, which includes the presence of open and sealed fractures, sealed fracture networks and crushed intervals. Characteristics for identification of BDZs, with special focus on rock conditions in Forsmark, are listed in Table A2-4.

In cases where geological indications are weak, identification of BDZs can be based primarily on geophysical and hydrogeological data. Significant transmissivity values over a borehole section together with limited geological indications might for example be sufficient to identify a BDZ, but all such interpretations will be assigned a low confidence level. It is essential to remember that there always needs to be geological support for a BDZ, even if it is weak.

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[8] Lönnqvist M, 2018. Potential for optimization of the repository layout at the Forsmark site: influence of low conductivity rock volumes. SKBdoc 1700389 ver 1.0, Svensk Kärnbränslehantering AB. (Internal document.)

Table A2-4. Geologic parameters, together with geophysical and hydrogeological data (if available) used for identifying BDZs.

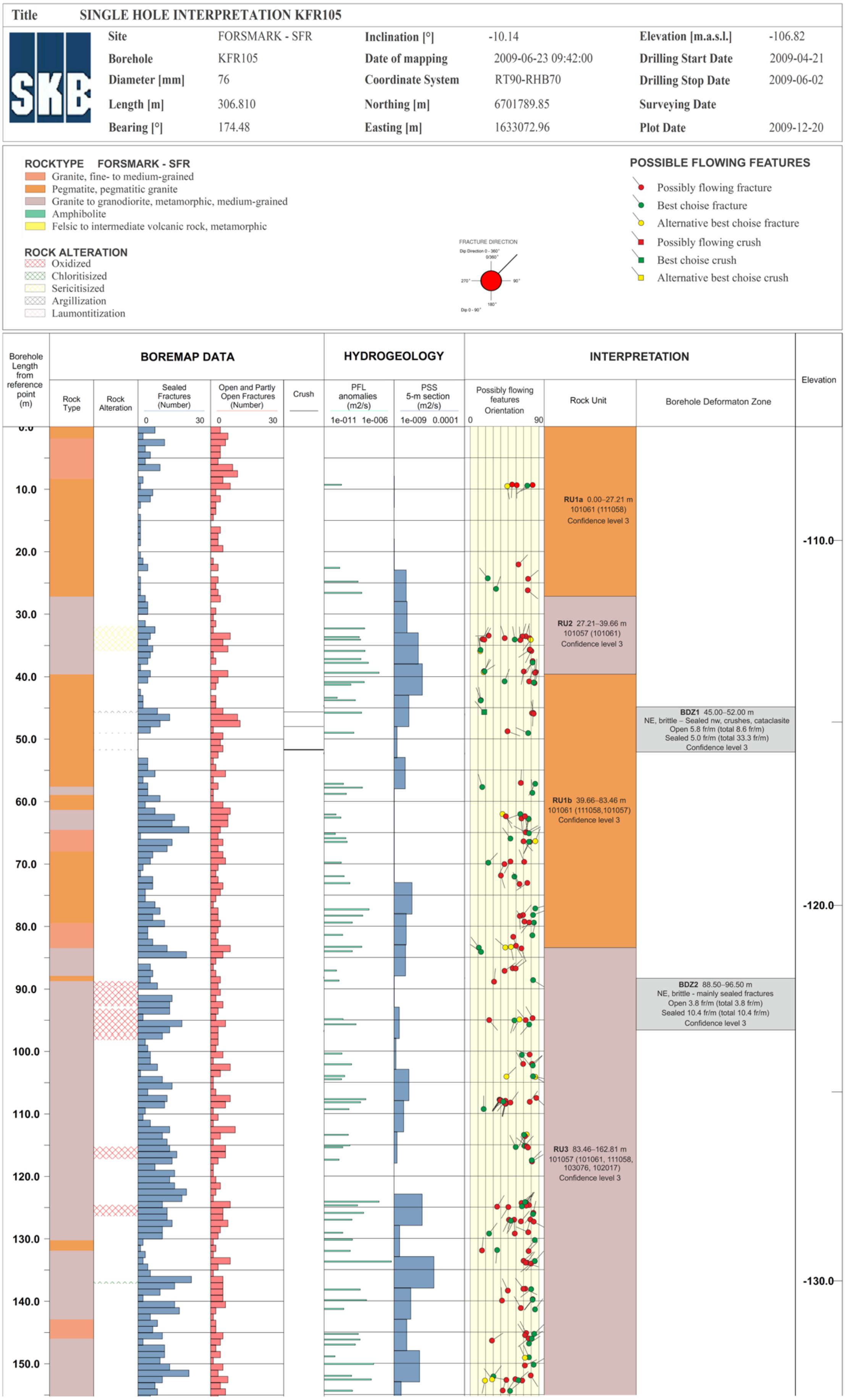
Parameter	Description
GEOLOGY	
Fracture frequency	Anomalously high frequency of sealed and/or open fractures, typically manifested as sealed fracture networks or crushed intervals
Hydrothermal alteration	Presence of intense rock alteration. Commonly red-stained bedrock due to sub-microscopic hematite dissemination of feldspars (mapped as oxidation), but indicative examples in Forsmark are quartz dissolution, epidotization, chloritization and argillization
Brittle fault rocks	Presence of fault gouge, cohesive or incohesive breccia and cataclasite
Ductile fault rocks	Presence of mylonite or phyllonite; conspicuous grain-size reduction
Kinematic indicators	Presence of shear striae or tectonic markers (intersecting pegmatite veins, etc), which indicate displacement. Also second order structures, such as en echelon tension gashes, Riedel shears, kinked terminations, and step-overs, are of interest, although the possibility to observe these features in a borehole is very limited
Fracture width (aperture for open fractures)	Existence of fractures with anomalous widths (apertures), where "anomalous" includes those widths (apertures) that exceed the minimum value registered during the borehole logging
GEOPHYSICS (if available)	
Resistivity	Anomalous decreased resistivity resulting from the existence of conductive fractures
Caliper	Caliper anomalies along incohesive borehole intervals
Sonic velocity	Decreased P-wave velocity in highly fractured or altered intervals
HYDROGEOLOGY (if available)	
Water inflows	Primarily assemblages of PFL anomalies with significant T_{PFL} values

Each BDZ and RU identified during the detailed GSHI procedure should be characterized according to the guidelines in Table A2-5, with arguments for identification. The result is also presented graphically, for example as a log plot (see Figure A2-6), displaying the interpretation alongside properties of inferred RUs and BDZs.

Table A2-5. Description characterized RUs and BDZs identified during the detailed GSHI.

Rock unit	Borehole deformation zone
Borehole length	Borehole length
Dominant rock types[1]	Deformation style
Subordinate rock types	Alteration
Deformation style	Fracture frequency
Alteration	Fracture surface properties
Fracture frequency	Fracture mineralogy
Confidence level	Orientations of fractures and deformational rocks (stereographic projections)
Comment	Occurrence of fault rocks
	Division into zone core and damage zone (incl. change in fracture frequency)
	Dominant rock type
	Focused resistivity
	P- and S-wave velocity
	Caliper anomaly
	Fluid temperature and resistivity
	Transmissivity from PFL (m^2/s)
	Pumping flow rate (l/min)
	Transmissivity from pumping test (m^2/s)
	Confidence level
	Comments (criteria for identification)

[1] For lithologically heterogeneous rock units that consists of two or more dominant rock types in largely equal proportions, the designation should include all dominant rock type components.



Title SINGLE HOLE INTERPRETATION KFR105

Site	FORSMARK - SFR	Inclination [°]	-10.14	Elevation [m.a.s.l.]	-106.82
Borehole	KFR105	Date of mapping	2009-06-23 09:42:00	Drilling Start Date	2009-04-21
Diameter [mm]	76	Coordinate System	RT90-RHB70	Drilling Stop Date	2009-06-02
Length [m]	306.810	Northing [m]	6701789.85	Surveying Date	
Bearing [°]	174.48	Easting [m]	1633072.96	Plot Date	2009-12-20

Figure A2-6. *Example of a detailed GSHI interpretation.*

Kinematic analysis

The kinematic analysis comprises a separate activity aiming to improve the conceptual understanding of deformation zones as a complementary input for deterministic modelling. The analysis is only intended for characterising BDZs identified with a high level of confidence. The analysis aims to detail the following properties within the BDZ:

- Orientation of fractures with shear sense (given by the Boremap data).
- Fracture mineralogy.
- Orientation of possible shear striations on the fracture plane (trend/plunge).
- Measurement of displacements (e.g. across rock contacts or veins).

A summary of the geological development of the zone should be included in the description. If possible, the summary should include kinematic relationships and relative age properties between fracture minerals. Support by petrographic analysis of thin-sections may be relevant in some cases.

The kinematic interpretation is included as part of the BDZ property tables derived during the detailed GSHI. An example of graphical presentations to be included in the property table is given in Figure A2-7.

A2.7 Naming system

BFZs, BDZs and RUs identified during the overview and detailed GSHI are numbered consecutively in the order they are identified. The numbering always begins at the start of each borehole.

The naming begins with BFZ, BDZ or RU, depending on type of GSHI, followed by its serial number, beginning from 1 at the top of each borehole. Rock units with similar properties in the same borehole are differentiated by letters (a, b, c…) as illustrated in Figure A2-8.

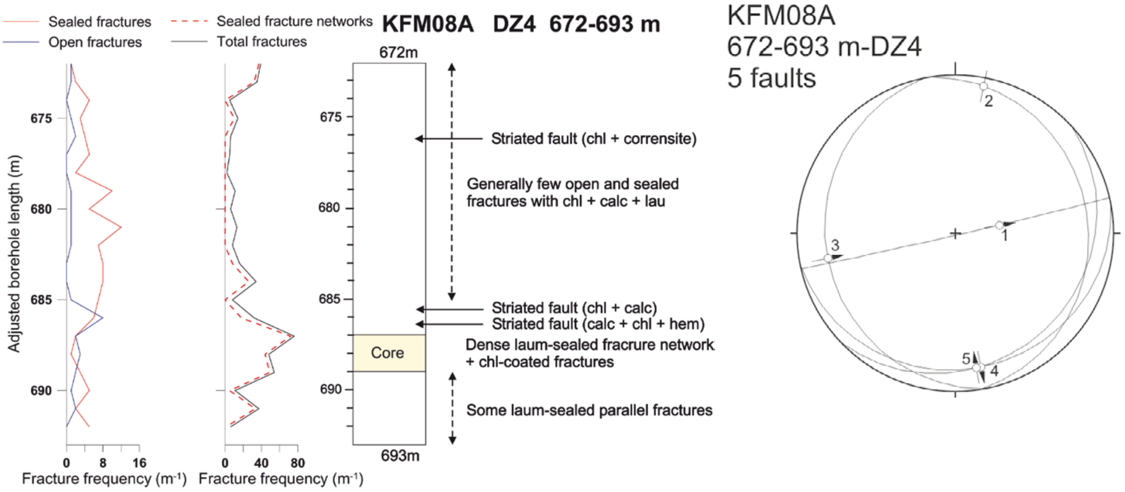


Figure A2-7. Example of a kinematical analysis of a BDZ identified with high confidence. From Nordgulen and Saintot (2006).

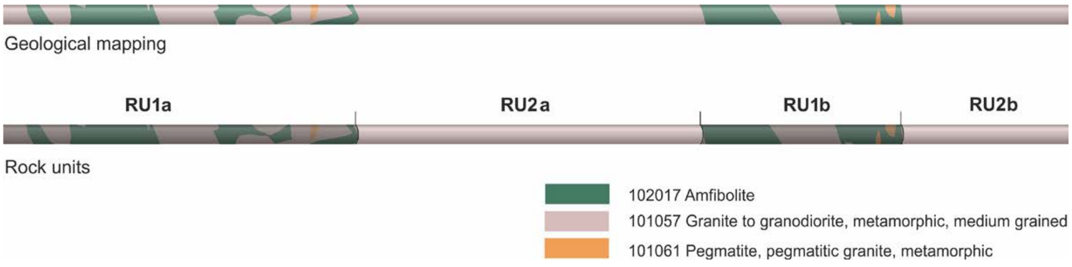


Figure A2-8. Example of naming convention for rock units.

A2.8 Confidence estimates in detailed GSHI

For the detailed GSHI, the confidence in the interpretation of BDZs and RUs is addressed by evaluating each object on a three-level confidence scale; high, medium and low. To avoid ambiguity, the application follows a number of principles, as exemplified in Table A2-6. Confidence levels are not applied in the overview GSHI.

For BDZs, the confidence in the interpretation concerns the identification of a structure as a borehole zone. For example, can the fracture network, crush or deformational rocks (e.g. breccia, cataclasite, mylonite) be of sufficient size to be qualified as a deformation zone? For RUs, the confidence level reflects the accuracy in the rock type determination and the relative homogeneity of their properties.

Table A2-6. Guidelines for estimating confidence for BDZs and RUs identified during the detailed GSHI.

Level	Rock unit (RU)	Borehole deformation zone (BDZ)
High	Readily distinguishable rock types or alterations, with homogenity in terms of mineralogy, grain-size, degree of ductile deformation and fracture intensity.	Structures with observable displacements with added support from fracture frequency and assessments of thickness and deformation intensity. Optionally, hydrogeological or geophysical data support the interpretation.
Medium	Vague, gradual contacts over several meters. Uncertanties in rock type identification. Some variations in mineralogy, grain-size or degree of ductile/brittle deformation.	Based on at least one significant geological property supported by other (weaker) geological indications.
Low	Heterogeneous mixtures of different rock types or alterations. Considerable variations in mineralogy, grain-size or degree of ductile/brittle deformation.	Limited indications that the selected structure constitutes a deformation zone. The interpretation is based only on weak geological indications or strong geophysical and hydrogeological indications.

A2.9 Handling, processing and storage

The results of the GSHI (BFZs, BDZs and RUs) are stored in SKB's database SICADA.

The quality control process for both overview and detailed GSHI consists of the steps in Table A2-7.

Table A2-7. Quality control process for overview and detailed GSHI.

Step	Quality control process	Responsible person
1.	Self-control of BFZs, BDZs and RUs and assembled property tables (see Tables A2-3 and A2-5).	Geologist responsible for assembling the multidisciplinary interpretation.
2.	Data delivery to SICADA for QA.	Geologist responsible for assembling the multidisciplinary interpretation.
3.	Peer-review and approval of BFZS, BDZs and RUs and assembled property tables (see Tables A2-3 and A2-5).	Site geologist (or designated person).
4.	Self-review of the detailed GSHI report.	Representatives for each discipline taking part in the detailed GSHI interpretation team.
5.	Peer-review and approval of the detailed GSHI report.	Site geologist (or designated person).

Appendix 3

Geological single-tunnel interpretation (STI)

Methodology for integrated synthesis of geological data from tunnels with support from hydrogeological and geophysical data

A3.1 Objectives and scope

The rationale for introducing the single-tunnel interpretation (STI) is to establish a methodology for integrating the geological, hydrogeological and geophysical information from a single tunnel to obtain the essential building blocks for assessing the main geological features and to prepare for a three-dimensional interpretation and modelling beyond the perimeter of the tunnel. The intention is to describe the geological features intersected by the tunnel as input to 3D modelling. Another application is the verification of existing models and model concepts.

The STI methodology aims to identify and describe TDZ and RU that intersects the tunnel, which are the smallest geological entities that *can* be associated with (1) structures defined as potentially critical for seismic reactivation and (2) volumes of possible relevance for the thermal modelling (cf Section 5.6 in the main report).

The minimum extent and true thickness of TDZs and RUs respectively, are discussed in the main report (Sections 5.4 and 5.5). Briefly, for rock types with anomalously low thermal conductivity, the minimum true thickness of a RU is in the order of 1–2 m according to Lönnqvist[9] whereas the TDZs is intended to capture deformation zones of such magnitude that they could exceed a diameter of 400 m (see Hökmark et al. 2019).

A fundamental aspect is that the entities identified and described by the STI remain fixed regardless of subsequent 3D geometric modelling activities. This independence from subsequent modelling activities or (hydraulic) time-dependent data or interpretations is made to retain full traceability to the original STI interpretation.

The STI-approach is analogous to the detailed single-hole interpretation (GSHI) methodology (Appendix 2). Compared to a borehole, an underground opening has a significant spatial extent and areal coverage, that allows acquisition of more three-dimensional geoscientific information and consequently gives more confidence in the geological interpretation. The STI therefore requires a more comprehensive analysis than the GSHI.

The result of the STI is 2D geometries of TDZs and RUs drawn on the 3D tunnel surface. Given the multidisciplinary aspects of the methodology, each interpreted TDZ and RU constitute a joint interpretation and conclusion of assembled geological properties with the support from hydrogeology and geophysics. In this context, it must be emphasized that geology always provides the foundation for the geometrical framework. Supportive information, if available, can come from hydrogeology or geophysics with the potential to reveal information beyond the tunnel perimeter.

The order of execution relative to the investigation, interpretation, and modelling sequence for the STI is illustrated in Figure A3-1.

Rock mechanical data are generally not considered in the interpretation of TDZs and RUs, but it is still important for subsequent integration work that specialists of the discipline participates in the STI exercise. This will provide both a thorough understanding of the tunnel section and a joint communication tool between the different disciplines.

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[9] Lönnqvist M, 2018. Potential for optimization of the repository layout at the Forsmark site: influence of low conductivity rock volumes. SKBdoc 1700389 ver 1.0, Svensk Kärnbränslehantering AB. (Internal document.)

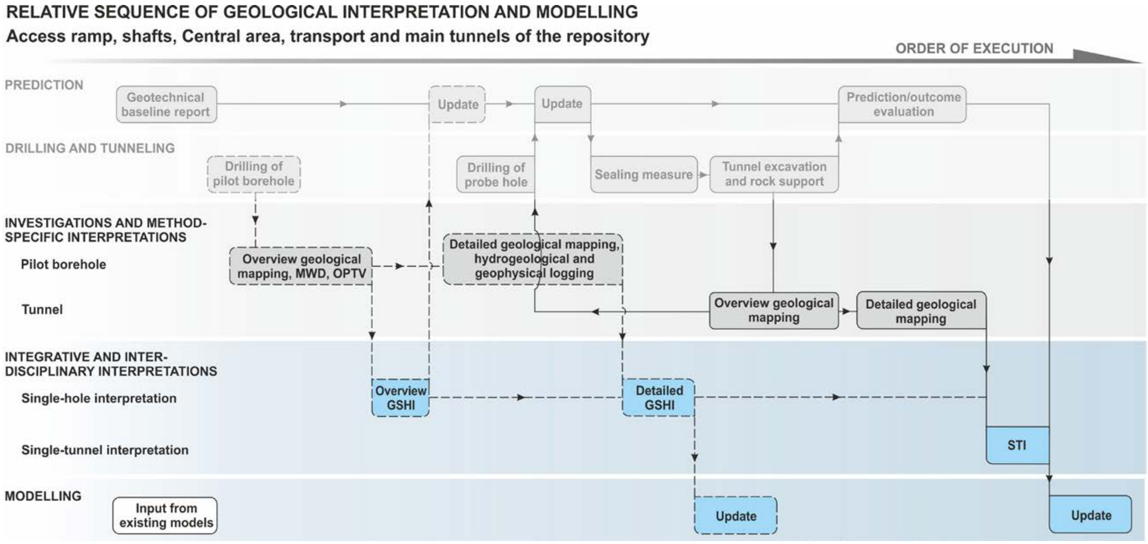


Figure A3-1. *The order of execution of the STI relative to other activities within the investigation, interpretation, and modelling sequence. Modelling is included to illustrate when action is recommended.*

A3.2 Applicability

The methodology is primarily intended to be used for tunnels in the deposition areas, where drilling and investigation of pilot boreholes are integral parts of the standard characterisation procedure, possibly with complementary geophysical tunnel investigations where such methods prove to be useful. The methodology is applicable in all types of outcrops, excavations and underground openings in the repository. The methodology requires that a detailed geological tunnel mapping exists. The STI methodology can be executed also on incomplete datasets, but with lower confidence.

The STI is carried out independently for each tunnel, with supplementary information from probe/grouting holes and associated pilot boreholes, where such are available. For longer tunnels, (i.e. tunnels longer than 300 m, such as sections of the main and transport tunnels), it may be more convenient to perform STIs covering sections of an entire tunnel, for example adjusted to lengths of associated pilot boreholes.

A3.3 General work procedure

The interpretation procedure is largely similar to the GSHI, and can be separated into five steps:

1. Compilation and visualization of necessary data.
2. Desktop assessment.
3. Multidisciplinary interpretation.
4. Tunnel visit by the interpretation team for examination and a more detailed characterization of kinematic indicators for high level confidence TDZs.
5. Description of identified TDZs and RUs.

Overview flowcharts of the sub-activities and products for the identification and characterisation of TDZs and RUs are presented in Figure A3-2. Details in the procedure must be tested and developed in practice, with a focus on how to execute the multidisciplinary integration work.

The STI is proposed to be carried out using RVS (Rock Visualization System) and RoCS (Tunnel Characterization System) developed by SKB. RoCS is closely integrated with SICADA which allows direct storage of geometries and properties from within the system. RVS is closely connected to SICADA which allows quick retrieval of RoCS, probe- and pilot hole data as well as geological models and individual geological objects essential to perform the STI analysis.

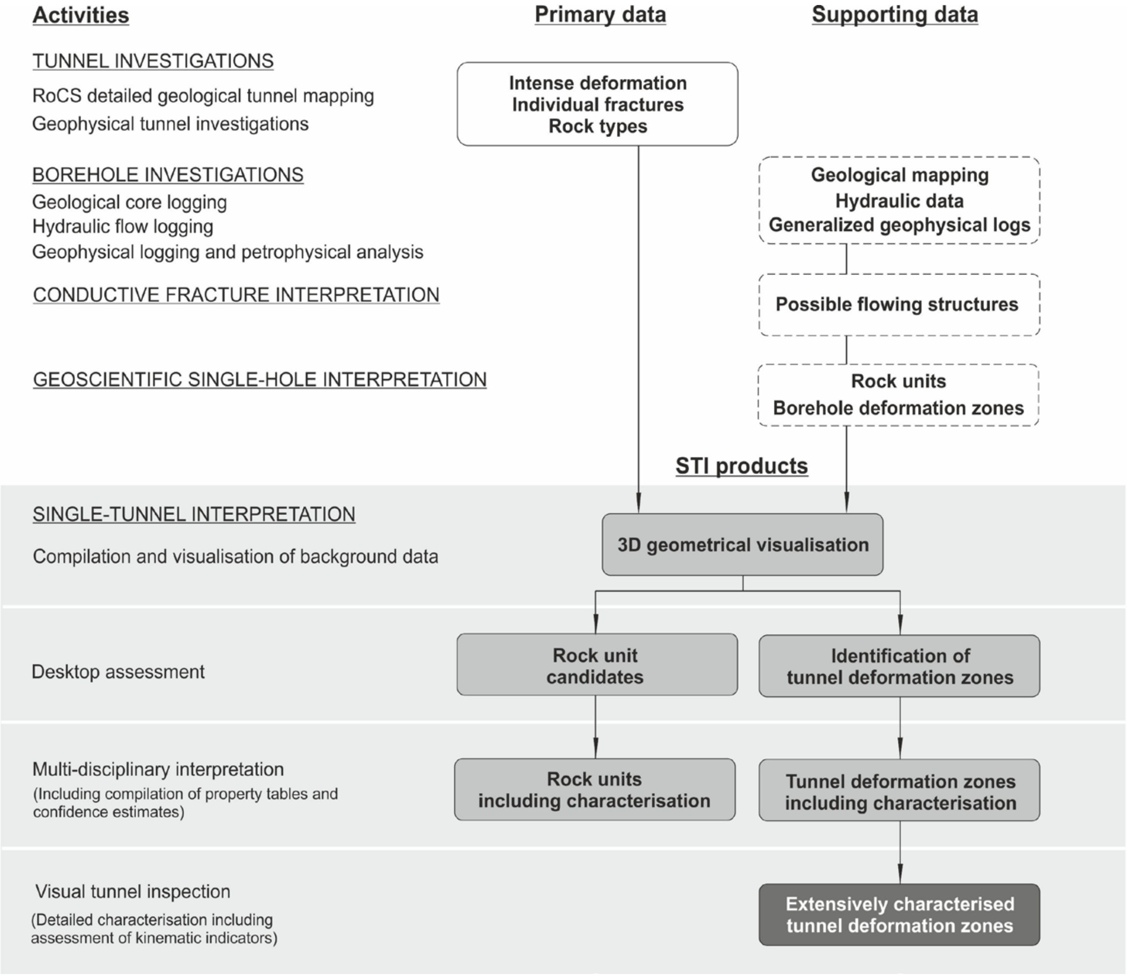


Figure A3-2. *Overview flowchart showing the STI procedure for identification and characterisation of rock units and tunnel deformation zones.*

The STI process is initiated in RVS by importing the detailed RoCS mapping and tunnel geometry for a selected section. If available, supportive information from a pilot borehole over the same tunnel section can be added to the visualization. If deemed relevant, BDZs and/or RUs from the detailed GSHI can be projected onto the mapped tunnel geometry. Based on this, a first desktop assessment is made to identify RUs and candidates for TDZs along the tunnel section. In addition, each data source is evaluated to identify sections of specific interest.

In the following step, an integrated analysis is carried out of TDZs and RUs established mainly from lithology and fracture data, with support from geophysics and hydrogeological data. It is important that this exercise also utilizes any site-specific understanding in the analysis. Conceptualisations of identified TDZs should be considered, describing internal distribution of fault core(s) and damage zones. The multidisciplinary analysis are reported as digitized areas and intersections of TDZs and RUs on the 3D model in RoCS.

Finally, the interpretation is reviewed by a visual inspection in the tunnel. Possible modifications after the review can, for example, include updates in the conceptualisation or extent of a structure. To support further 3D modelling, this step should also include an assessment of kinematics for any identified TDZs. The resulting geometries of TDZs and RUs and their corresponding geological description is registered in RoCS and delivered to SICADA.

A3.4 Compilation and visualization of background data

The basis for the STI are the detailed geological mapping data provided in RoCS (see Section 3.1.2 in the main report). Thus, the input consists of rock types, fractures, areas of intense deformation and observed inflow mapped on the tunnel perimeter. Depending on availability, supporting data may also come from pilot boreholes and probe-/grouting holes over the same tunnel section and the corresponding detailed GSHI. The pilot hole also provides hydrogeological, rock mechanical and petrophysical properties to identified TDZs and RUs in the tunnel. The input to the STI analysis is summarised in Table A3-1, along with identification of the applicable SKB method descriptions.

All available data is visualized in RVS. If pilot borehole data and detailed GSHI exist, this can be visualized together with the RoCS mapping and tunnel geometry. Also, hydraulic data collected along pilot and probe/grouting boreholes, and interpretations of tunnel geophysics can be added to the visualisation.

Table A3-1. Input to the STI analysis, along with the SKB method descriptions for performance of the investigation activities.

Data from routine tunnel investigations:	
Geological mapping using RoCS	SKB MD 150.011
Photogrammetric background images used for mapping	SKB MD 150.010
Drilling from probe and/or grouting boreholes	–
Hydraulic tests in probe holes	SKB MD 341.016
Supporting data/results from pilot borehole investigations:	
Detailed geological logging using Boremap	SKB MD 143.006
OPTV borehole imaging	SKB MD 222.006
Geophysical borehole logging	SKB MD 221.002
Pseudogeological interpretations of borehole geophysics	SKB MD 221.003
Registration of flush and return water parameters for underground core drilling	SKB MD 640.010
Difference flow logging	SKB MD 341.013 SKB MD 341.021
Hydraulic single-hole tests	SKB MD 341.016
Geophysical tunnel investigations:	
Seismics – Reflection seismic profiling, Refraction seismics and TSP	–
Resistivity and Mise-a-la-masse	SKB MD 212.005
Existing interpretations:	
Geoscientific single-hole interpretation of pilot borehole	Appendix 2

A3.5 Execution

Rock units

Rock units are defined by their dominant rock types and their thermal properties, with possible support from geophysics. The extent of individual RU should be as large as the rock type distribution, fracture intensity and degree of ductile deformation possibly allows with respect to the need to identify thermally anomalous units in the deposition areas.

The tunnel surface is divided into individual RUs to obtain a complete surface coverage along the tunnel. Each RU may correspond to a single rock occurrence (i.e. rock type surface), such as amphibolite or several rock types of similar composition, alteration or degree of ductile deformation. An example of a geometrical representation from a real tunnel section is shown in Figure A3-3.

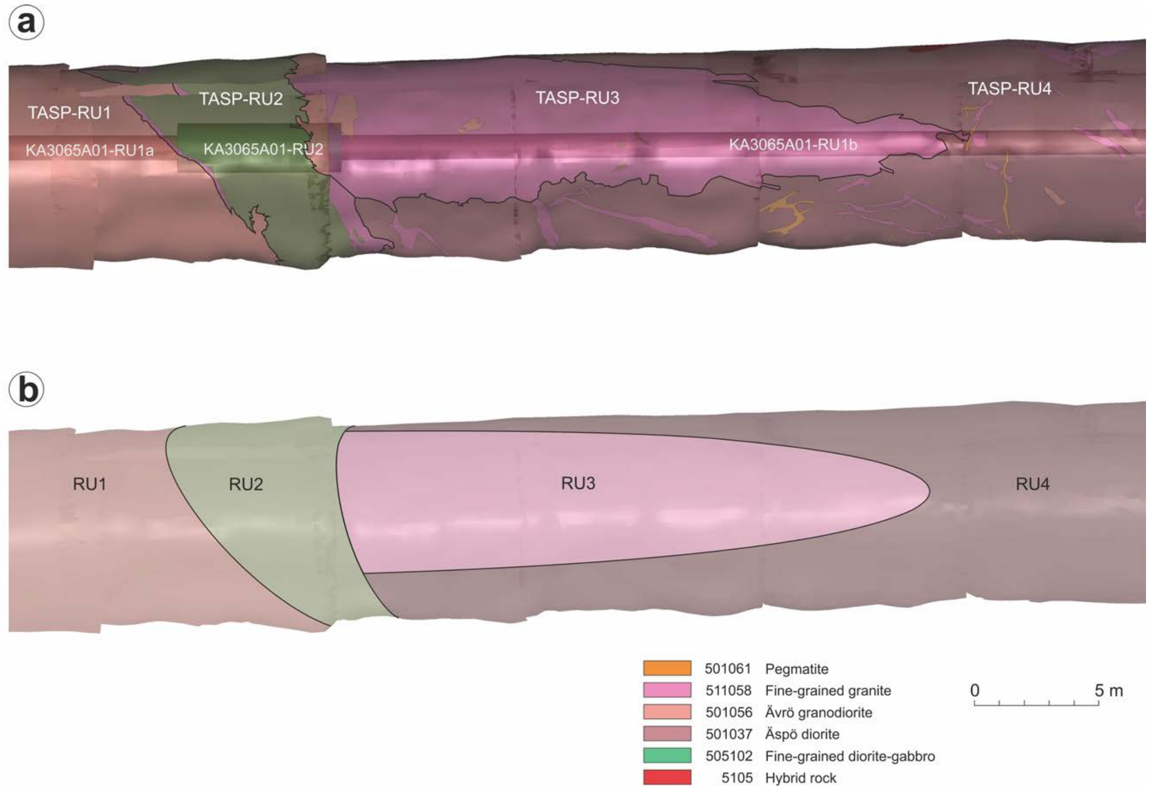


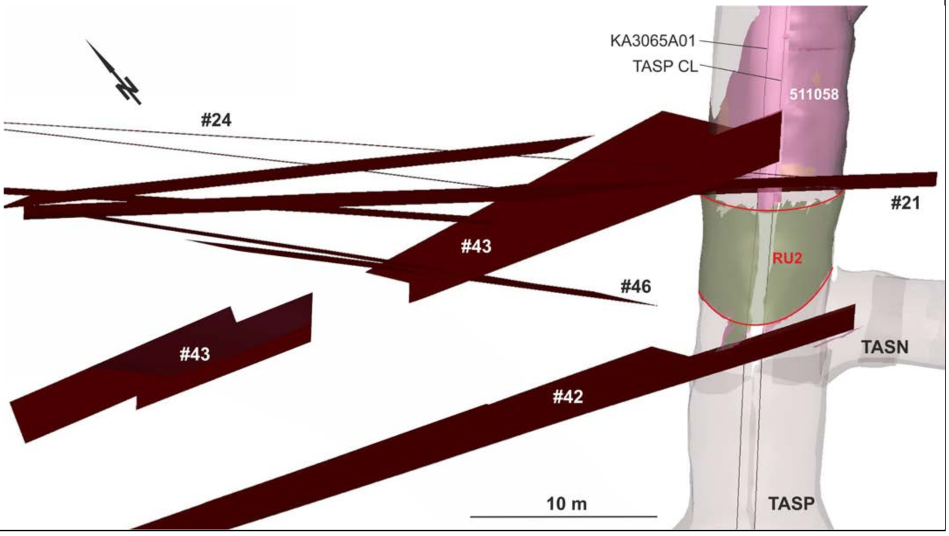
Figure A3-3. *The components of RU division exemplified by an oblique top view towards northwest of a section along a tunnel in the Äspö HRL. a) Initially four RUs are identified based on the rock type mapping (RU1 to RU4). Also shown is the RU distribution from a detailed GSHI from a pilot borehole, where RU2 is represented by a wider cylinder than the other two borehole units. b) Final representation of a simplified geometry of four RUs.*

Desktop assessment

A desktop assessment is initiated in RVS by importing the detailed RoCS mapping and tunnel geometry for the specified section. If available, supportive information from a pilot borehole over the same tunnel section can be added to the visualization and, if deemed relevant, RUs from the detailed GSHI.

An assessment of possible RUs is presented by the coordinating geologist as discussion material for the multidisciplinary team, in the format of notes on each identified RU and visualizations from RVS, either directly in the model or as printout drawings along the tunnel section, as exemplified in Table A3-2.

Table A3-2. Example of a desktop assessment along a tunnel in the Äspö HRL. For additional geometrical details see Figure A3-3.

Tunnel length (centre line)	39.6–43.0 m	Deformation style	Massive
Dominant rock type	505102	Wall-rock alteration	Fresh
Subordinate rock types	511058, 501056	Contacts	Simplified planar 304°/45°, 320°/65°
		Comment	–
Correlated GSHI RUs in pilot borehole KA3065A01			
RU2	14.25–20.83 m	505102, subordinately 511058	
Tunnel seismics	Possible geometric coincidence with several reflectors (#21, 24, 42, 43 and 46), see figure below, though the visibility is generally low. Two reflector sets can be identified: 1. NW–SE striking (towards TASU), sub-vertical dips. 2. WNW striking (towards TASA), steeply dipping towards NNE. Whether one or both of the sets originates from the contacts of the fine-grained diorite-gabbro (505102) is not conclusive. 		

Multidisciplinary interpretation

During the multi-disciplinary interpretation, the desktop assessment is reviewed in detail by the discipline specialists (geology, hydrogeology and geophysics). Specifically, correlations between supportive data is assessed (such as RU from a pilot borehole geophysical anomalies).

Each RU is defined by its geometrical extent on the tunnel surface together with an integrated property table describing its character, cf Table A3-3. Much of the input to the property table is geometrical information that can be extracted from the desktop assessment (cf Table A3-2). The confidence level in terms of identification certainty and homogeneity is assessed for each RU during the multidisciplinary interpretation.

Table A3-3. Integrated property table for the characterisation of rock units (RUs) identified during a multidisciplinary STI.

Tunnel	TASP
Name	RU2
Chainage from (m)	39.6
Chainage to (m)	43.0
Dominant rock type	505102
Subordinate rock type 1	511058
Subordinate rock type 2	501056
Rock contacts	Simplified planar 304°/45°, 320°/65°
Deformation style	Massive
Wall-rock alteration	Fresh
Fracture intensity (P_{21} based on RoCS, m/m^2)	0.2
Correlations	KA3065A01:RU2, seismic reflector 42, 43
Confidence level	High
Comments	

Tunnel deformation zones

The identification process for deformation zones is complex and requires a combined evaluation of key properties linked to the zone extent or size, including mechanical instability. The primary component in this process is evaluating FPI structures identified during the RoCS tunnel mapping (see main report, Section 1.5 for FPI definition). As some FPIs may not be detected in the initial RoCS mapping, as exemplified in Figure A3-4, it is important to also evaluate the combined effect of all geological characteristics such as splays, fracture trace gaps and densely fractured tunnel sections as well as reviewing areas with limited coverage in corners and abutments.

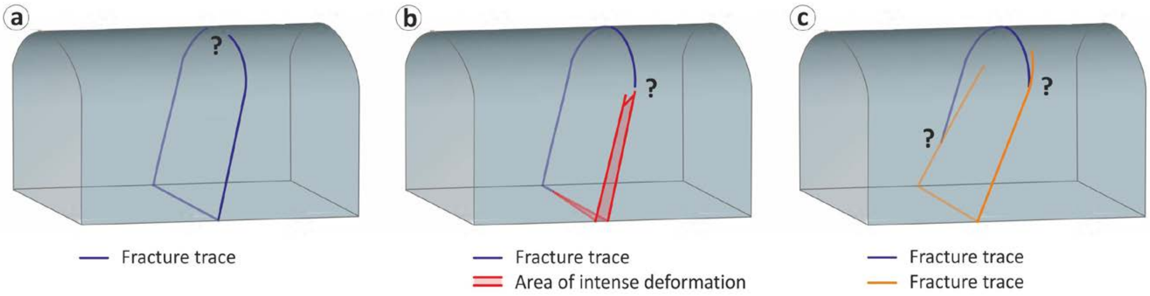


Figure A3-4. Examples of FPI candidates that might escape detection during the geological tunnel mapping: (a) Fracture trace with a mapped break which might be attributed to cut effects or shadows, (b) an area of intense deformation that appears to continue as a facture trace, and (c) fracture traces that appear to splay into or truncate each other.

The evaluation of TDZs shall include one or more of the following characteristics:

- Fault core with an anomalous high frequency of fractures, commonly in the form of complex networks, and the occurrence of fault gouge, cohesive or incohesive breccia and cataclasite. Intense rock alteration may also be indicative.
- Kinematic displacement with shear striae and tectonic markers, such as intersecting veins, etc. In a composite brittle deformation the displacement is likely to be partitioned between several parallel/sub-parallel fractures with a net displacement that is less than along a single fracture plane of the same size. In addition, several second order structures may exist, such as en-echelon tension gashes, Riedel shears, kinked terminations, and step-overs. Fracture roughness can also be of interest for evaluating potential movements.
- Fracture aperture and the potential existence of grout.
- Significant hydraulic inflow through the structure.

Applicable descriptors of TDZs can be dependent on site-specific conditions and should also be evaluated considering the conceptual understanding of deformation zones in Forsmark. An analysis made at ONKALO in Finland by Nordbäck (2014), showed that the most typical properties of fractures with an interpreted size > 50 m are slickensides, thick fillings of certain minerals, water leakage and associated alteration, closely linked to specific orientations and rock types.

An example of a composite data set proposing the existence of a TDZ is presented in Figure A3-5.

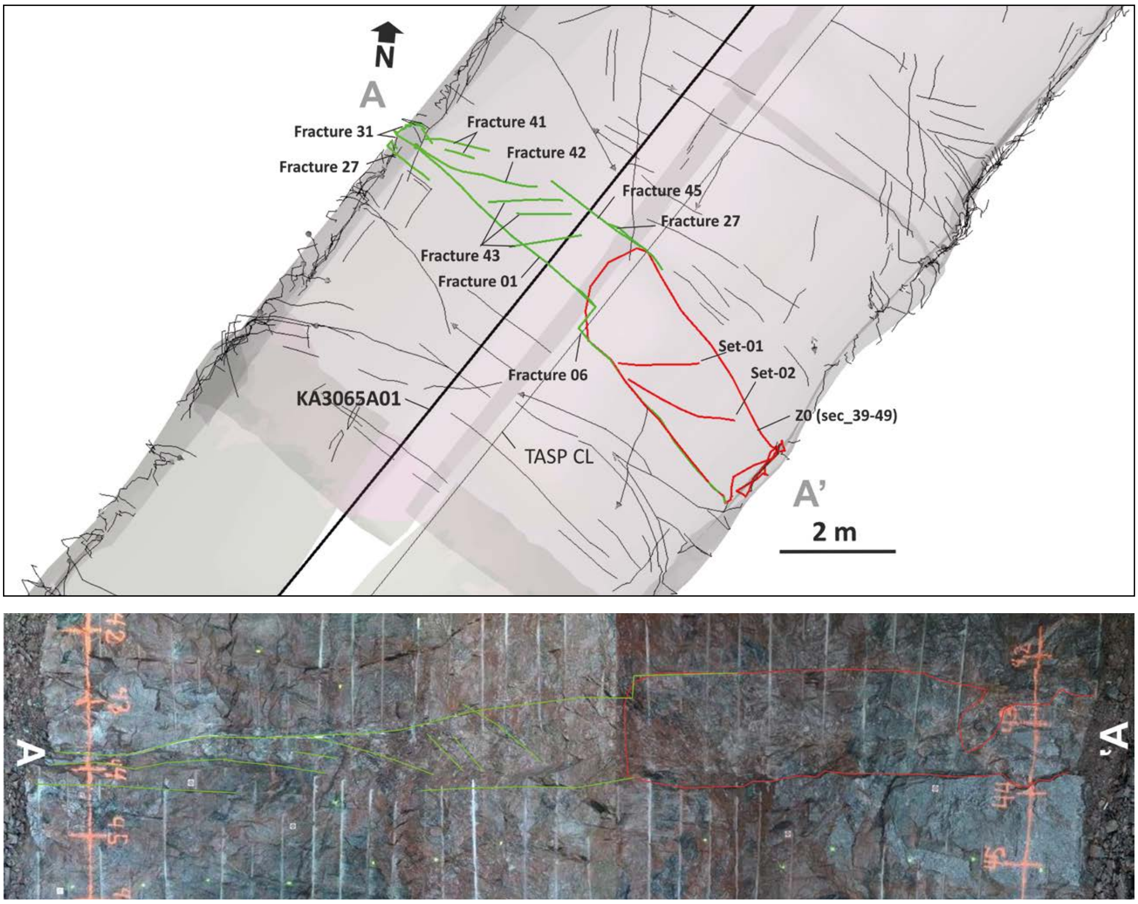


Figure A3-5. Top view of fractures and areas of intense deformation along the ceiling and walls in a tunnel in the Äspö HRL. A composite structure along the section A–A', consists of an area of intense deformation (red in south–eastern half of the tunnel) that continues as an array of individual fractures in the north–western half of the tunnel (marked in green). Bottom: plan view of the structure (A–A').

Desktop assessment

A desktop assessment is initiated in RVS by importing the detailed RoCS mapping and tunnel geometry for the specified section. If available, supportive information from a pilot borehole over the same tunnel section can be added to the visualization and, if deemed relevant, BDZs from the detailed GSHI.

Identified structures that may be TDZs is drawn on the tunnel surface in RoCS (Figure A3-6). The analysis is presented in the format of notes on each identified TDZ and visualizations from RVS, either directly in the model or as printout drawings along the tunnel section as exemplified in Figure A3-6 and Table A3-4.

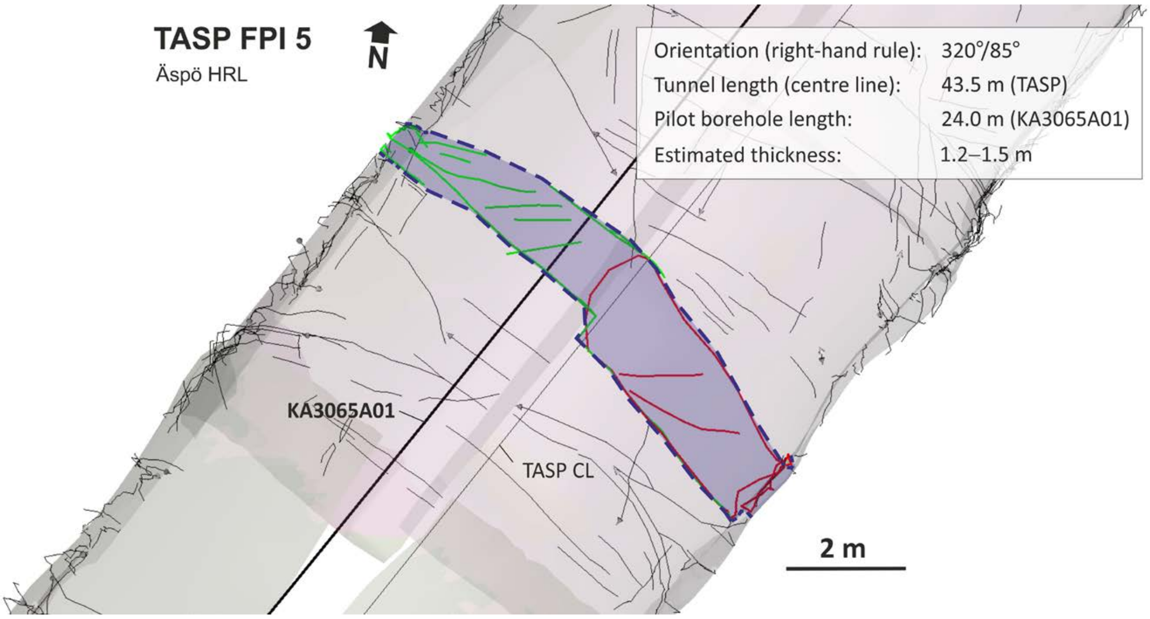


***Figure A3-6.** Plan view (ceiling and walls) of a proposed TDZ along a tunnel in the Äspö HRL. The TDZ extent is drawn on the tunnel surface in RoCS. See Figure A3-5 for additional details on the structure.*

Table A3-4. Example of the desktop assessment describing the geological interpretation. For additional geometrical details see Figure A3-5 and Figure A3-6.

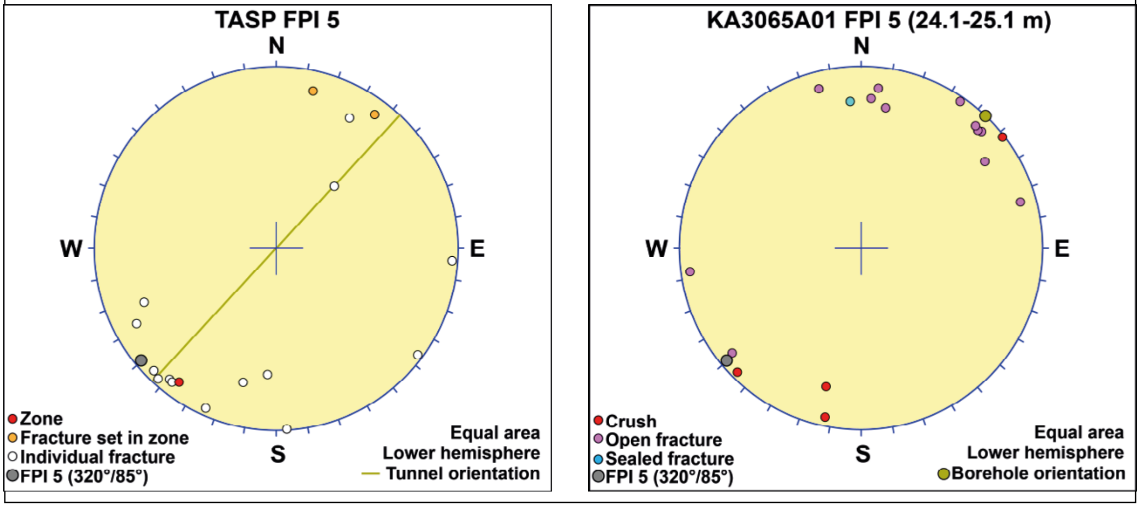
Deformation style	Brittle. Locally brecciated.
Internal structure	Fulfils FPI criterion. An area of intense deformation that continues as an array of individual fractures in the north–western part of the tunnel.
Alteration	No associated bedrock alteration.
Pilot borehole (KA3065A01)	No identified SHI borehole deformation zone. Increased frequency of open fractures in the interval 24.17–25.03 m, which coincides with the occurrence of a fine-grained granite (511058). Structure orientation largely parallel with the fractures in the tunnel. Crushed section at 24.19–24.30 m. Weak oxidation throughout the interval of increased fracture frequency.

Basis for identification

1. A composite structure that includes an area of increased fracturing.
2. Evidence for faulting by local brecciation.

RoCS objects

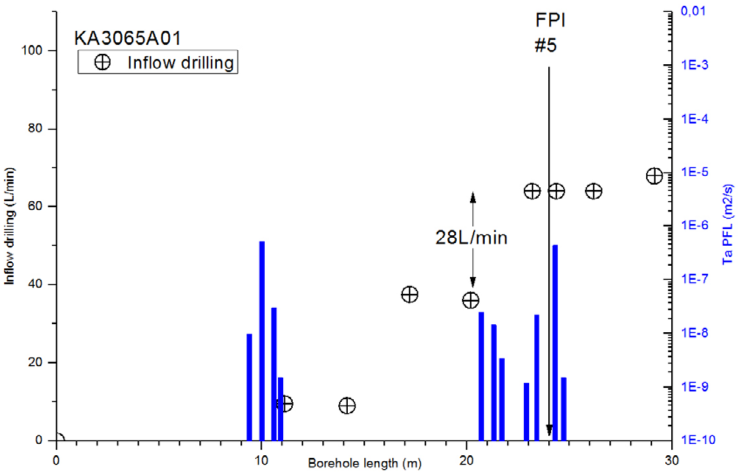
Sec_39–47 m	Z0 (Set-01 and Set-02)	Increased fracturing bounded by Fractures 06 and 07
	Fracture 06	The fracture runs across the the roof and forms the outer part of Z0
	Fracture 07	Thin fracture zone 1–5 cm wide, locally with breccia
	Fracture 27	Width is 0.5 mm
Sec_38–58 m	Fracture 01	Aperture ≤ 2 mm, width 5–50 mm. Partly calcite sealed breccia. The fracture branches into sub-parallel fractures
	Fracture 27	2 fractures. Width 0.3 mm
	Fracture 28	Width 0.5 mm
	Fracture 39	3 separate traces. 4 fractures with 8–15 cm spacing. Width 0.3–1 mm
	Fracture 41	Width 0.5 mm
	Fracture 42	Width 0.5–2 mm
	Fracture 43	2 separate traces. Several parallel fractures with 1–3 dm spacing. Width 0.3 mm



Proposed TDZs can be evaluated in light of observed intervals with inflow and flowing structures from available data sources (probe/grouting holes, pilot holes or in tunnel sections). Also, hydraulic responses from nearby boreholes can be used to support the evaluation.

Discipline-specific hydrogeological characterisation of a proposed TDZ is presented in Table A3-5.

Table A3-5. Example of a TDZ desktop assessment describing hydrogeology.

Tunnel (TASP)	Average 40 drops/minute from several points extending along the deformation zone and associated fractures.
Probe holes	Responses at 7.54 m during probe hole drilling of TASP21 are correlated to the structure.
Pilot borehole (KA3065A01): Drilling did not show any inflow at 24 m (the location of the structure), but considering its width it is feasible that a closely situated inflow of 28 L/min is originating from this structure. Flow logging using PFL indicates a somewhat more transmissive (4×10^{-7} m^2/s) inflow at 24.3 m.	

If geophysics are available, information can be used to support the identification of TDZs by correlation to anomalies that may correspond to structural features. Geophysical anomalies are not necessarily restricted to a specific tunnel of interest but can support the STI process also in nearby tunnels.

If available, geophysics in the pilot borehole can be utilized together with the tunnel geophysics to correlate more distal anomalies (beyond the tunnel periphery). Indirect observations through geophysics can support the interpretation of potentially critical structures running parallel or sub-parallel to the tunnel, without tunnel/borehole intersections (i.e. EFPC-structures).

However, usage of geophysical methods is expected to be limited, considering the relatively high uncertainty in correlating inferred anomalies with geological features.

Geophysical desktop assessment of a proposed TDZ could include the following information as illustrated in Figure A3-5 and Figure A3-6, which is further exemplified in Table A3-6:

- Geometries and interpreted geophysical significance of inferred seismic reflectors.
- Resistivity and/or velocity anomalies revealed in tomographic images relative to the interpreted FPI.

Table A3-6. Example of a desktop assessment describing geophysics along a tunnel in the Äspö HRL.

Tunnel seismics	Inferred geometric coincidence with Reflector #47, although the visibility is low. Also Reflector #24 coincides quite well with the FPI, which could indicate that the reflectors originate from same structure. However, it cannot be excluded that Reflector #24 is a result of the contact between fine-grained diorite-gabbro (505102) and Ävrö granodiorite (501056).
Pilot borehole (KA3065A01)	Weak geophysical anomalies in density, seismic velocity at interval 23.19–24.5 m. A weak anomaly in the synthetic seismogram suggests that a reflector is possible.

Multidisciplinary interpretation

During the multi-disciplinary interpretation, the desktop assessment is reviewed in detail by the discipline specialists (geology, hydrogeology and geophysics). If available, any supporting information from geophysics or hydrogeology is used to adjust or add to the TDZ interpretation. Specifically, correlations between supportive data is assessed (such as BDZ from a pilot borehole geophysical anomalies).

Each TDZ is defined by its geometrical extent on the tunnel surface, its orientation (cf Figure A3-6), and an integrated property table describing its character (cf Table A3-9). Much of the input to the property table is geometrical information that can be extracted from the desktop assessment (cf Table A3-4). The confidence level in terms of identification certainty, geometrical extent and orientation is assessed for each TDZ during the multidisciplinary interpretation.

If geophysical anomalies are included in the interpretation, there always need to be a geological or hydrogeological explanation such as association to groundwater, significant changes in material properties, internal structure and/or mineralogy. This also includes information on spatially associated structural/lithological features and artefacts that may mask geophysical detection.

Although geology always form the backbone in the interpretation, indications of TDZs may also come from significant water inflows without obvious correlation to candidates identified on geological basis. A decision on whether a structure can be identified as TDZ may require a renewed examination in the tunnel, if accessible. It is important that the final interpretations, including alternatives, are mutually agreed by all involved disciplines.

If a geophysical interpretation allows extrapolation of the structure into the surrounding rock mass a correlation is needed with geological or hydrogeological interpretations as exemplified in Table A3-7.

Table A3-7. Correlation of geophysics with geological and hydrogeological interpretations for a TDZ along a tunnel in the Äspö HRL.

Basis for geophysical correlation

The size, mineralogy (existence of chlorite and clay minerals) and associated water may allow for recognition using both seismic and resistivity measurements. The deformation is relatively focused to a well-defined, locally brecciated structure with few splays. There are no obvious structural or lithological features in the tunnel that will interfere with the geophysical interpretation/correlation. A cross-cutting occurrence of fine-grained granite (511058) has a distinctly different orientation and any genetic relationship can be excluded.

Reflector #47, and to some extent reflector #24, matches well with the structure (represented by the blue disc), both based on the geometry and location. It is inferred that the reflector #47 shows the continuation of the structure and allows extrapolation to TASU (not shown) with a high level of confidence with the following geometrical estimates:

- Estimated minimum size (diameter) is > 50 m (the distance between TASP and TASU)
- Orientation: strike 138° ± 5° (right-hand rule), dip 85° ± 2°

A complete property table for a TDZ is presented in Table A3-8 as result of the integrated synthesis:

- Details of individual structures or lithological boundaries that are inferred to make up the TDZ, including stereographic projections (content of Figure A3-6 and Table A3-4).
- Integrated interpretation between geology, geophysics and hydraulics (Table A3-5 and Table A3-6) including indications beyond the tunnel (as exemplified in Table A3-7).

A confidence level is assigned based on the overall assessment of the TDZ interpretation (Table A3-9).

Table A3-8. Example of an integrated property table for a TDZ along a tunnel in the Äspö HRL.

Tunnel	TASP
Name	TDZ043
Tunnel deformation zone (TDZ)	Yes
Tunnel chainage (centreline, m)	43.5
Estimated thickness (m)	1.5
Orientation (right-hand rule)	320°/85°
Deformation style	Brittle. Locally brecciated
Internal structure	Fulfils FPI criterion. A deformation zone that continues as an array of individual fractures in the north–western part of the tunnel
Alteration	None
Fracture frequency (from available drilling, m^{-1})	3.2
Water	Average 40 drops/minute from several points extending along the deformation zone and associated fractures
Correlations	KA3065A01: no BDZ, increased fracture frequency, crush 24.2–24.3 m KA3065A01: inflow at 24.3 ($T = 4 \times 10^{-7}$ m^2/s) Probe holes: Responses at 7.54 m during probe hole drilling of TASP21 are correlated to the structure Seismic reflector #47
Confidence level	High
Comments	A TDZ focused to a well-defined, locally brecciated structure with few splays. Based on reflector #47 an estimated minimum size (diameter) is > 50 m (the distance between TASP and TASU)

Visual inspection in the tunnel

If unobstructed tunnel surfaces are available (i.e. not covered with shotcrete), a visual inspection by the interpretation team should be carried out. Changes to the interpretation are adjusted in the STI documentation.

A3.6 Naming system

Each tunnel in the repository is identifiable by its name, such as deposition tunnel DA09 or the main tunnel (DA00). RUs and TDZs are named by its consecutive number from the beginning of each tunnel, e.g. in deposition tunnel DA09, the numbering of RUs starts with RU001.

By using the combination of tunnel name and the naming of each RU or TDZ it is possible to selectively search through all assembled STI interpretations.

A3.7 Confidence level

Confidence on a three-level scale is estimated based on the overall assessment of the interpretation of RUs and TDZs. To avoid ambiguity, the application of this system follows the principles in Table A3-9.

For RUs the confidence level reflects the accuracy in the rock type determination and the homogeneity of their properties. For TDZs, the confidence in the interpretation concerns the spatial extent and the data that support its possible extrapolation.

Table A3-9. Guidelines for estimating confidence level for RUs and TDZs identified during the STI procedure.

Level	Rock unit (RU)	Tunnel deformation zones
High	Readily distinguishable rock types or alterations, showing homogenity in terms of mineralogy, grain-size, degree of ductile deformation and fracture intensity.	FPI structures with observable displacements plus added support from assessments of thickness and deformation intensity. Optionally, hydrogeological or geophysical data from the tunnel and/or a pilot borehole support the interpretation.
Medium	Vague, gradual contacts over several metres. Uncertanties in rock type identification. Some variations in mineralogy, grain-size or degree of ductile/brittle deformation.	FPIs identified with high confidence plus support by other (weaker) geological indications.
Low	Heterogeneous mixtures of different rock types or alterations. Considerable variations in mineralogy, grain-size or degree of ductile/brittle deformation.	Limited geological indications, such as thin, insignificant or discontinuous structures defined without being mapped as FPIs (e.g. existence detected by geophysics).

A3.8 Handling, processing and storage

In the interpretive stage of the STI, RVS is used to visualize available 3D data. Simultaneously the detailed geological mapping is loaded into RoCS. RVS is then used to review the data in 3D whilst the interpreted extents of RUs and TDZs are drawn directly in RoCS.

Properties are entered according to Table A3-3 (RUs) and Table A3-8 (TDZs). Finally, the results are uploaded to SICADA.

A STI report is assembled at convenient length intervals with documentation from the desktop and the multidisciplinary assessment.

The quality control process for the STI consists of the steps in Table A2-7.

Table A3-7. Quality control process for the STI.

Step	Quality control process	Responsible person
1.	Self-control of geometries of TDZs and RUs and assembled property tables (see Table A3-3 and Table A3-8) uploaded from RoCS to SICADA.	Geologist responsible for assembling the multidisciplinary interpretation.
2.	Peer-review and approval of TDZs and RUs and assembled property tables (see Table A3-3 and Table A3-8).	Site geologist (or designated person).
3.	Self-review of STI report.	Representatives for each discipline taking part in the STI interpretation team.
4.	Peer-review and approval of STI report.	Site geologist (or designated person).

Appendix 4

Model components and properties attributed to modelled geological objects

A4.1 Object type

A 3D geological model typically contains deformation zones and rock or fracture domains bounded by the model constraints and the bedrock surface. Depending on the modelling purpose, it can also contain geometries for the regolith (layers) and topography. In addition, the model may contain engineered structures such as boreholes, tunnels, and underground openings.

The object library is used for storing the 3D modelled geological objects. Table A4-1 describes the types of modelled objects that can be entered into the object library. Currently, only modelled surface and volumetric objects can be stored in the library. This means that all information used as support for the modelling, such as borehole and tunnel geometry, data, interpretations as well as lineaments and seismic reflectors cannot be included as objects into the object library. The location and geometries of engineered structures such as boreholes, tunnels or other underground openings are essential in the modelling process. Generally, these objects are either accessed directly through SICADA or as design models of planned or constructed tunnels and caverns made available as input to the modelling process like other primary data.

Table A4-1. Geological object types that can be entered into the object library. Currently the object library only supports surface and volume objects.

Object type	Geometry	Comments
Topography and/or seafloor	Triangulated mesh surface	Boundary object with no requirements for entering properties
Rock surface	Triangulated mesh surface	Boundary object with no requirements for entering properties
General surface object (such as a conformity or other surface)	Triangulated mesh surface	Description required to explain type
Fracture surface	Triangulated mesh surface	–
Deformation zone	Triangulated mesh surface describing a closed volume	The volume describes the zone thickness and includes a calculated "mean" centre surface as part of the object.
Rock domain	Triangulated mesh describing a closed volume	–
Fracture domain	Triangulated mesh describing a closed volume	–
General volume object (such as a water body or overburden)	Triangulated mesh describing a closed volume	Description required to explain type

Initially the modelled geometrical objects only contain spatial information to describe their location, shape, and extent. To obtain a classification they need to be assigned an *object type* and a *unique name for identification*. As previously described in Munier et al. (2003), object types can be thought of as a descriptor of an object displaying a group of geoscientific parameters, which together describe the geological character of the element, for example, a geological structure.

The assignment of an object type informs what the object represents, and hence which characteristics can be used to describe the object. Only one object type can be defined for each geometrical object. Properties are assigned for the whole area or volume of the modelled object. If this is not appropriate, the object may be subdivided into smaller parts or be populated with aggregate statistics that describes the object.

The fundamental metadata that are required for each object are summarised in Table A4-2. Using RVS as a modelling tool, all these metadata are automatically generated upon creation or editing of an object in the library.

Table A4-2. Mandatory metadata required for every entry into the object library.

Mandatory metadata required for all geological objects		
Geological Object Type	See Table A4-1	
Geological Object Name	General form: [Type prefix][Site prefix][incremental number][suffix if needed] Example: ZFM4001, RFM46	New deformation zones identified from sub-surface investigations shall have the prefix of ZFM and a continuous numbering starting from 4001. Sheet joints are identified with the prefix JFM starting with number 001. A suffix can be used if needed. New domains identified from sub-surface investigations shall have a prefix of RFM (rock domains) or FFM (fracture domains) and shall have a continuous numbering following the previously used numbering in SDM-Site.
Creator	Name	Based on a list of accredited modellers.
Editor	Name	Based on a list of accredited modellers.
Version number	Ex. 1.D1 [geometry version].D[description version]	The geological description version number (Dx) is independent from the geometry version number (cf Section 5.2.2 of the main report).
Date, Time	[YYYY-MM-DD], [Hr:Min]	

A4.2 Geological properties for zone and domain objects

A geological description of a modelled object is necessary so that the character and geological understanding, the relationship to other geological objects, and the basis for interpretation are fully transparent. This description comprises a list of properties that accompanies the geometry of a modelled object. The properties shall be assigned to the whole object geometry and not on a node-by-node basis. For the previously developed site-descriptive models, these descriptions were presented as property tables in modelling reports. For future work, a database storage of property descriptions is strongly proposed to facilitate successive editing, either in an independent database engine or along with the geometries in the object database.

Geological objects and their corresponding properties are one unified item from a user perspective, although the digital data handling solution might be that object geometry and properties is stored in different environments. Edits to the geometry or property descriptions shall result in a version update according to Table A4-2. Property description compilations for each object in the object database should be stored in a database from which tables, diagrams and logs can be easily exported and compiled for various purposes. Excellent examples of suitable formats of deformation zone and rock domain catalogues can be found in Curtis et al. (2011) and Stephens et al. (2007).

For each geological object type there is a set of key properties that are considered essential for describing and understanding the object and its relation to its environment. Table A4-3 and Table A4-4 present the properties that are required for the description of deformation zones and rock domains, respectively. The property tables should, where possible, be accompanied with illustrations, graphs, pictures to further enhance the understanding of the object. An example of a deformation zone property table that includes the necessary properties is presented in Figure A4-1.

The required properties needed in a description of a fracture domain are shown in Table A4-5. In addition to these geometric properties further knowledge is generally needed to directly use these properties for understanding/analysing groundwater flow, contaminant transport or rock mechanical behaviour.

The object type specific properties can be divided into a) geological properties and characteristics, b) geometrical properties, c) object constraints, d) basis for modelling and e) confidence assessment of the object.

Geological properties and characteristics are quantitative and/or qualitative descriptions of the geological object such as geological character, deformation style, alteration, fracture character etc and/or distributions or ranges of such properties. Object geometry describes the modelled geometrical properties of the object such as orientation, length thickness etc. Object constraints describe the geometrical relationships between the modelled object and the surrounding space, such as terminations or boundaries to other objects. The basis for modelling is a listing of observations used for the object identification that primarily includes intercepts with boreholes, tunnels and outcrops identified during the single-hole and single-tunnel interpretations. Other observations can be inferred such as lineaments, seismic reflectors, and, more rarely, primary data sources. Finally, the property tables contain a confidence assessment of the modelled object as well as its properties.

Practical methods to assign/attribute quantitative and qualitative properties to modelled geological objects were developed successively during the preceding site descriptive modelling. The method developed at an early stage of the site investigations (Andersson et al. 1996, 1998) was successively refined in the final stages of the site investigations in Forsmark (Stephens et al. 2007; Wahlgren et al. 2008), and subsequently also in the development of the SFR-PSU model (Curtis et al. 2011), to meet requirements from users of the geological model for purposes of repository design and safety performance.

Table A4-3. Properties for deformation zone objects.

Geological character

Deformation style: Brittle, brittle-ductile or ductile, direction of slip or slip vector.

Sense of Displacement: Described in terms of slip direction (e.g. normal, reverse, sinistral and dextral). If there is more than one slip direction it must be stated.

Alteration: Type and degree of alteration.

Fracture character: Main fracture character, including general orientation and fracture types (open, sealed, crushes, sealed networks etc).

Confidence estimates: Based on the principles presented in Chapter 6 of the main report, where the confidence of each deformation zone (total object CL) is described in terms of four categories, each divided into two subcategories. Estimates for each subcategory are addressed by a three-level confidence scale: (1) low, (2) medium and (3) high, with a total confidence obtained as a sum of the estimates for the individual types. In addition, each individual property listed under the heading Geological character are assigned a property confidence level based on the three-level scale.

Object Geometry

Strike/dip: xxx°/xx° (right-hand-rule).

Estimated horizontal length (m): Estimated horizontal length of the deformation zone without reference to model boundaries. Total horizontal length of the deformation zone trace interception with the ground surface and for zones that never reach the ground surface, the maximum modelled horizontal length. The span is a judgement based on all the available data, considering the geometrical guidelines for extrapolation (see Section 5.4.7 in the main report). For deformation zones with trace interceptions with the ground surface, the span is defined by a review of the magnetic data with consideration to the lineament continuity and extent.

Model thickness (span)(m): The average distance between the two triangulated mesh surfaces that have been modelled to envelop all outcrop, borehole, tunnel target intercepts. The quoted span is based on the minimum and maximum orthogonal (to the strike direction) thickness of the deformation zone geometry, which is modelled with variable thickness.

Object constraints

Listing of how the object extends and truncated to other objects or to a boundary. Information include:

- Truncations in z-direction
- Upper and lower bounds
- Truncations in the direction of strike
- Dependencies to other objects.

Ex. ZFMNEXXXX truncations:

- Upper bound: surface
- Lower bound: −600 m a.s.l. (volume of interest)
- Blind termination in the SW direction
- Truncated against ZFMNWXXXX in the NE direction

Table A4-3. Continued.

Basis for modelling

Outcrops: Observation points (PFM00xxxx), trenches and excavations (AFM00xxxx) at the ground surface.

Boreholes: HFMxx, KFMxx, HFRxx or KFRxx. Target interval (xxx–xxx m), Fix point (xxx m), GSHI BDZ (BDZxx xxx–xxx m and confidence level) and Geometrical interval (xxx–xxx m).

Tunnels: ID code for underground opening. Target interval (xxx–xxx m), Fix point (xxx m), STI TDZ (TDZxx xxx–xxx m and confidence level) and Geometrical interval (xxx–xxx m).

Fix point is typically the centre of the Target interval. Normally target intervals and GSHI BDZ or STI TDZ intervals are identical but, in certain cases, they may differ due to other factors being involved in the overall interpretation. Target and Geometrical interval differ usually slightly and, in some cases, there are no corresponding Target interval defined, due to weak of geological indications.

Lineaments: MFMxxxx, XFMxxxx or MSFRxxxx. Weight (An overall assessment of the confidence of the linked lineament.).

Seismic reflector: Axx–Jxx, Rank (certainty of the observation on the profiles on which the reflection is observed).

Modelling procedure

A short outline of the basis for the modelled geometry representing the deformation zone.

Fracture characteristics

Fracture orientation: Stereograms of fractures and other structural elements of the geological mappings along Target intervals, with corrections for orientation bias in contoured plots. Besides individual fractures, this includes the following structures:

- Boremap data for boreholes – internal structures of crushes, sealed networks and fault rocks (SICADA parameters STRIKE3, STRIKE4, DIP3 and DIP4).
- RoCS data for tunnels – deformation zones including fracture sets.

Main cluster orientations are presented as main orientation direction specifying the mean pole and the dispersion.

Fracture frequency: Mean fracture frequency m^{-1} plots for the deformation zone based on one or several borehole or tunnel intercepts corrected for orientation bias. Open/partly open and sealed fractures in boreholes are quoted separately.

Fracture RQD: RQD plots based on one or several tunnel and borehole intercepts. Tunnels and boreholes are quoted separately.

Fracture mineralogy: A histogram of mineral coating or mineral filling along fractures inside a deformation zone based on one or several borehole and tunnel target intercepts. Tunnel and borehole intercepts are shown separately, with a separation of open/partly open and sealed fractures in boreholes.

Individual intercepts: Stereograms (fractures and other structural elements of the geological mappings) and logs along individual Target intervals.

Hydraulic interpretation

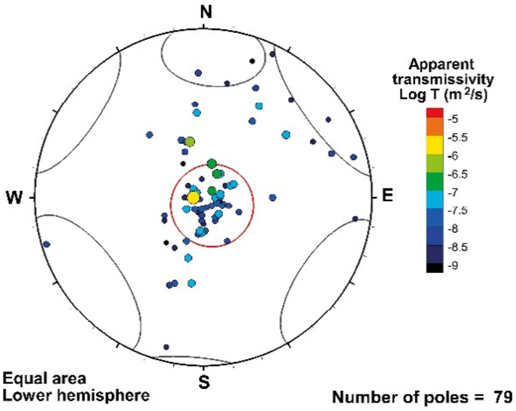
Hydraulic width: x m. Average hydraulic width calculated as the average true thickness (intersection-angle compensated) of all intercepts.

No of intercepts: Number of intercepts with hydraulic data that are judged representative for the zone.

$T_{eff}(0)$: x m^2/s. Effective transmissivity at z = 0. Calculated as the geometric mean of all intercept transmissivities T(z) after a depth-trend compensation to z = 0. Below, T_0 is short for T(z = 0) or T(0).

Log $T_{eff}(0)$: x, σ = y. Common logarithm of the effective transmissivity at z = 0 and the standard deviation (y) of all log T(0) values, respectively.

The standard deviation in modeled logarithmic transmissivity values is estimated as (log $T_{0,max}$–log $T_{0,min}$)/4 (i.e., assuming that the range in evaluated log T_0 corresponds to ± 2 σ).



Stereogram illustrating PFL-f data orientation colored and scaled by apparent specific transmissivity. The term apparent transmissivity is used to emphasize that measurements may be subject to upstream hydraulic chokes. Hard sectors representing fracture set clusters and orientations of boreholes and the modelled deformation zone are included as reference.

Calculation procedure: A short outline of the basis for the calculation procedure.

Table A4-4. Properties of rock domain objects.

Geological Character

Rock Domain Composition

Dominant rock type: Type and quantitative proportion.

Subordinate rock type: Quantitative proportions of subordinate rock types.

Degree of homogeneity: Low, medium and high.

Metamorphism/alteration: Type and degree of alteration.

Mineral fabric and tectonic foliation: Description of the orientation pattern based on stereographic projections and whether there is a spatial dependency in the domain. Main cluster orientations are presented as main orientation direction specifying the mean pole and the dispersion.

Confidence estimates: Based on the principles presented in Chapter 6 of the main report, where the confidence of each domain (total object CL) is described in terms of four categories, each divided into two subcategories. Estimates for each subcategory are addressed by a three-level confidence scale: (1) low, (2) medium and (3) high, with a total confidence obtained as a sum of the estimates for the individual types. In addition, estimates of the internal rock type distribution and petrographical properties are assigned a confidence level based on the three-level scale.

Character of dominant rock type

Mineralogical composition: xx % for dominant rock type. Range/mean/standard deviation/number of samples.

Grain size: According to the standard scheme of Geological Survey of Sweden.

Structure and texture: According to the standard scheme of Geological Survey of Sweden.

Density: xxxx kg/m^3. Range/mean/standard deviation/number of samples

Porosity: xx %. Range/mean/standard deviation/number of samples.

Magnetic susceptibility: xx SI units. Range/mean/standard deviation/number of samples.

Electric resistivity: xxxxx ohm m in fresh water. Range/mean/standard deviation/number of samples.

Uranium: xx ppm based on gamma ray spectrometry data. Range/mean/standard deviation/number of samples.

Natural exposure rate: xx microR/h. Range/mean/standard deviation/number of samples.

Object Geometry

Object volume (m^3)

Listing of how the object extends and truncated to other objects or to a boundary. Information include:

- Constraints from boundaries (surface, extent of model volume).
- Dependencies to neighbouring objects.

Basis for modelling

Outcrops: Observation points (PFM00xxxx), trenches and excavations (AFM00xxxx) at the ground surface.

Boreholes: HFMxx, KFMxx, HFRxx or KFRxx. Target interval (xxx–xxx m), GSHI RU (RUxx xxx–xxx m and confidence level) and Geometrical interval (xxx–xxx m).

Tunnels: ID code for underground opening. Target interval (xxx–xxx m), STI RU (RUxx xxx–xxx m and confidence level) and Geometrical interval (xxx–xxx m).

Normally target intervals and GSHI RU or STI RU intervals are identical but, in certain cases, they may differ due to other factors being involved in the overall interpretation. Target and Geometrical interval differ usually slightly due to simplifications of object geometries.

Modelling procedure

Conceptualisation and ground for compilation into a rock domain, together with a short outline of the basis for the modelled geometry.

Table A4-5. Properties for describing the geometrical properties of fracture domain objects. Details on how these properties are derived can be found in Selroos et al. (2022) and are not covered in this report.

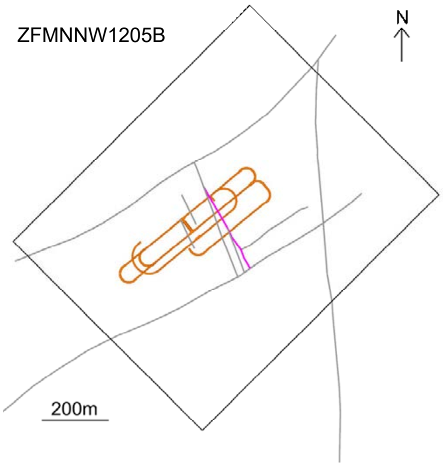
Fracture types	Proportion of open, sealed, partly open.
Orientation distribution	See Selroos et al. (2022)
Fracture size distribution	See Selroos et al. (2022)
Fracture Intensity distribution	See Selroos et al. (2022)
Spatial Distribution	Their relative position in space. See Selroos et al. (2022)
Fracture terminations	How generations of fractures cross each other. See Selroos et al. (2022)
Basis for modelling	**Outcrops:** Observation points (PFM00xxxx), trenches and excavations (AFM00xxxx) at the ground surface. **Boreholes:** HFMxx, KFMxx, HFRxx or KFRxx. Target interval (xxx–xxx m), GSHI RU (RUxx xxx–xxx m and confidence level) and Geometrical interval (xxx–xxx m). **Tunnels:** ID code for underground opening. Target interval (xxx–xxx m), STI RU (RUxx xxx–xxx m and confidence level) and Geometrical interval (xxx–xxx m). Normally target intervals and GSHI RU or STI RU intervals are identical but, in certain cases, they may differ due to other factors being involved in the overall interpretation. Target and Geometrical interval differ usually slightly due to simplifications of object geometries.
Modelling procedure	Conceptualisation and ground for compilation into a fracture domain, together with a short outline of the basis for the modelled geometry.
Object constraints	Listing of how the object extends and truncated to other objects or to a boundary. Information include: – Constraints from boundaries (surface, extent of model volume). – Dependencies to neighbouring objects. – Fracture domains can overlap other volumes.

NNW	**ZFMNNW1205B**	Version number **D3**	Total Object CL **21**

GEOLOGICAL CHARACTER		Property CL
Deformation style:	Brittle, mainly steeply dipping fractures	3
Sense of displacement:	Reverse	1
Alteration:	Local reddening (oxidation) of faint to medium intensity	3
Fracture character:	Mainly NNW-SSO striking (foliation parallel), sealed fractures	2

OBJECT GEOMETRY	
Strike/dip:	153°/79° (right-hand-rule)
Length:	284 m (at ground surface)
Mean thickness (span):	4 m (2.7–4.6 m)

GEOMETRICAL CONSTRAINTS		Constrained
Upper:	Ground surface	X
Lower:	–280 m	–
Strike direction:	ZFMENE0159A	X
Opposite strike direction:	ZFMENE1061A, ZFMNNW1205A	X
Observed intersections:	AFM001393, KFM08B, KFM13, KFM21	



BASIS FOR MODELLING

Outcrops: AFM001393. True thickness of 2.7 m. CL assigned at outcrop interpretation = 3.

Boreholes:

Borehole	Target and geometric intercept							Inferred true thickness [m]	Comment
	PDZ	CL	Sec_up [m]		Sec_low [m]		Fix [m]		
KFM08B	1	2	133	128.70	140	142.88	136	4.6	–
KFM13	1	1	37	45.29	49	52.00	–	3.7	No fix point
KFM21	3	2	86	86.53	95	94.35	90.5	2.9	–

Tunnels: –

Lineaments: MFM2168G with an inferred extension towards NNW to connect with MFM2169G before truncation against MFM2054G0. CL assigned at lineament interpretation = 2.

Seismic indications: Intersects seismic profile LFM001021, but no associated low velocity anomaly exists.

MODELLING PROCEDURE

Originally modelled on the basis of outcrop and borehole data from the investigations of the shallow rock mass in the drift area where the zone was named ZFMNNW2168. Later renamed to ZFMNNW1205B in the FPS-Access model (Follin 2019).

ZFMNNW1205B is inferred to be a foliation parallel splay or sister to ZFMNNW1205A developed as second order structures due to displacements along ENE-trending zones.

Projected towards depth based on three borehole intercepts, where KFM13 PDZ1 is shared with ZFMNNW1205A. Fix points are consequently used for KFM08B PDZ1 and KFM21 PDZ3. Cut-off depth based on the ground surface trace length.

NNW	ZFMNNW1205B	Version number	D3	Total Object CL	21

OBJECT CONFIDENCE ESTIMATE

Category	Object CL	Argument
Interpretation		
Data source	*3*	*Outcrop AFM001393*
Results of interpretation	*3*	*High confidence observation in AFM001393*
Information density		
Number of observation points	*3*	*5*
Distribution of observation points	*3*	*Rather even distribution*
Interpolation		
Geometry	*3*	*One geometric alternative*
Geological indicators	*3*	*Interpolation supported by key geological parameters*
Extrapolation		
Dip direction	*1*	*No constraints. Based on ground surface trace length*
Strike direction	*2*	*Conceptual constraints against other structures*

HYDRAULIC INTERPRETATION

No of intercepts: 3

T_0: $1.6\cdot10^{-6}$ m^2/s

Log T_0: -5.8 $\sigma = 1.2$

Parameterisation of log T_0 in earlier models: Not modelled in Forsmark v. 2.3

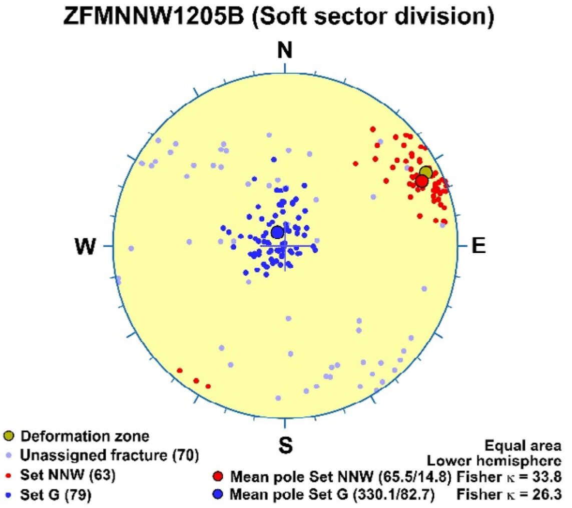
Calculation procedure: T_0 is calculated as a mean value of all three borehole intercepts. The estimated detection limit has been used for measured values below that limit.

FRACTURE CHARACTER

Orientation:
(right-hand-rule)
Set NW: 155°/75°
Set G: 060°/07°

Frequency: Boreholes: KFM08B, KFM13, KFM21

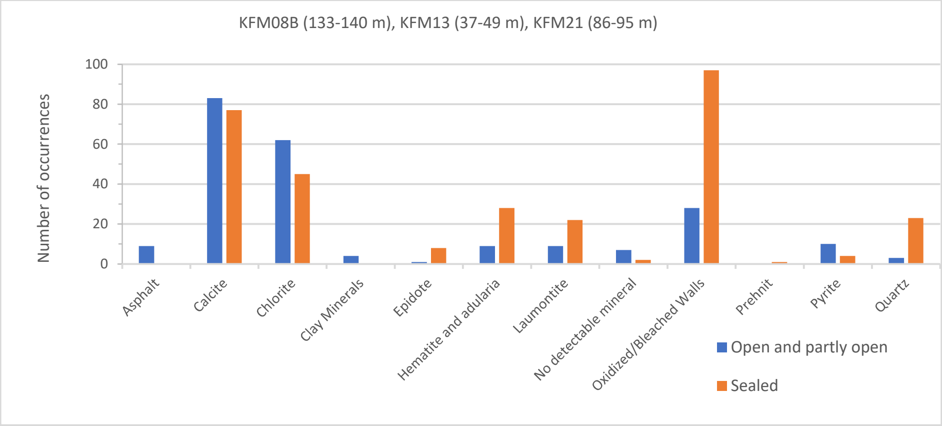
Fracture type	Terzaghi-weighed P_{10}
Open and partly open	3.5
Sealed	5.4
Sealed network	4.0
Crush	–



NNW	ZFMNNW1205B	Version number	D3	Total Object CL	21

RQD (span): 93 (78–100)

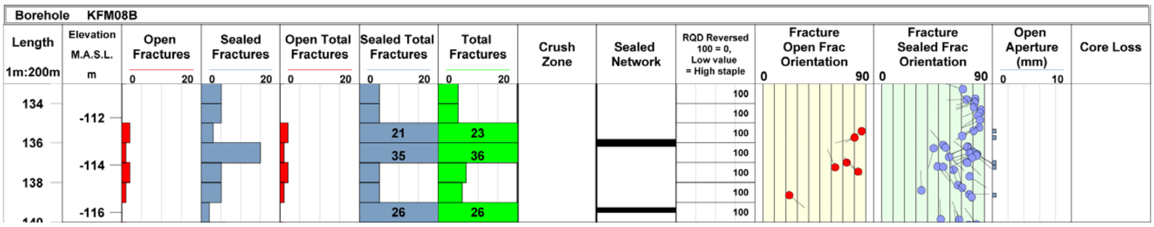
Filling:

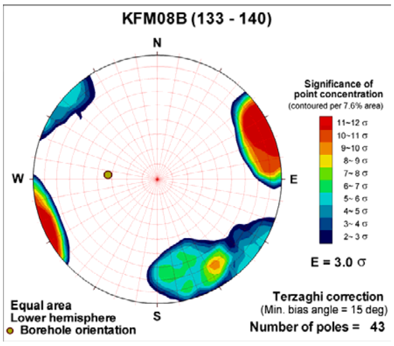


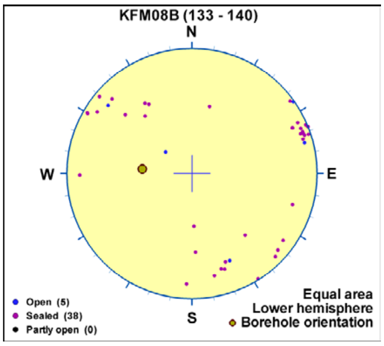
Comments: Mainly NNW-SSO striking (foliation parallel), sealed fractures, which dip steeply towards the west. Apertures generally less than 0,5 mm, with a few up to 5 mm. Local displacements along chlorite coated fracture planes with striations and slickensides. Clay minerals occurs subordinately, predominantly as corrensite.

INDIVIDUAL INTERCEPTS

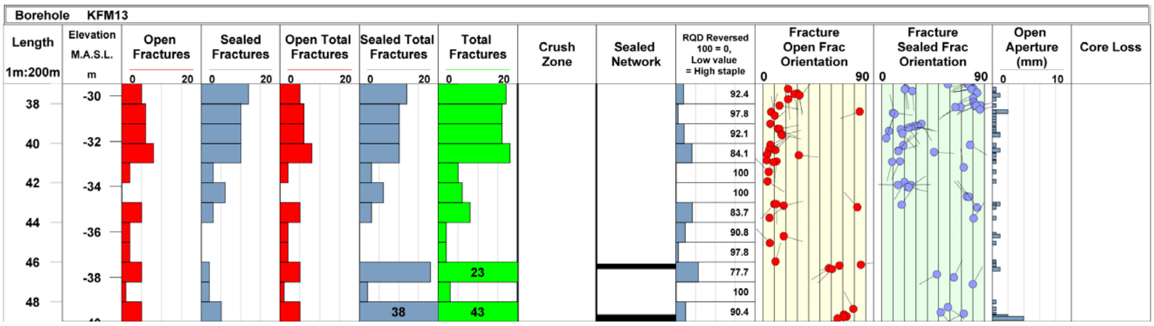
KFM08B PDZ1 (133–140 m)







KFM13 PDZ1 (37–49 m)



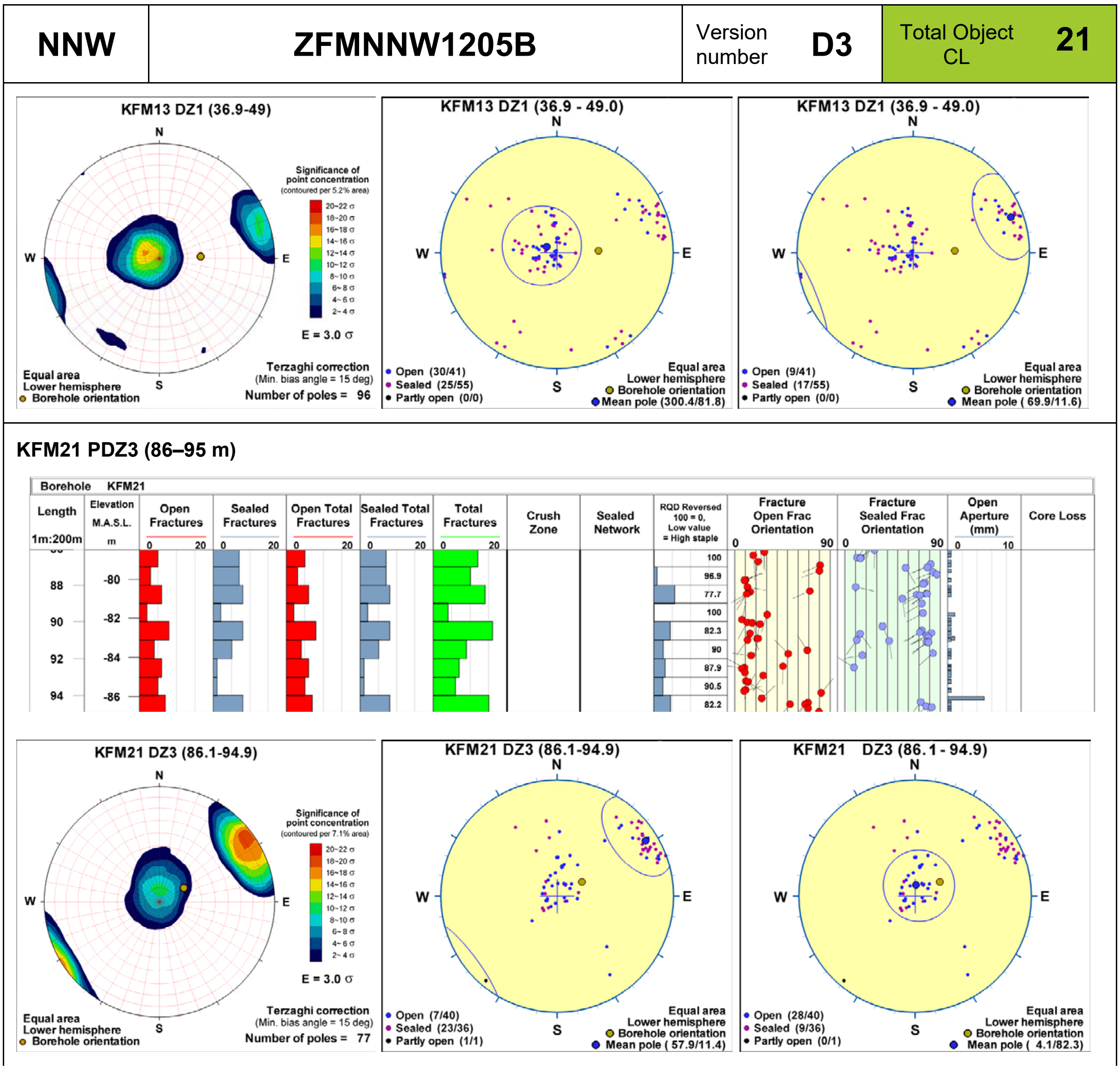


Figure A4-1. An example of a deformation zone catalogue for ZFM1205B, which presents geological, hydrogeological and mechanical properties with confidence estimates. CL = confidence level.

Appendix 5

Review procedure for the geological modelling

A5.1 Review procedure

Two types of reviews are carried out in connection with deliveries of individual objects and models (i.e. the assemblage of several objects in a defined volume): (1) Object review and (2) Model review. The object review is part of the continuous modelling process and shall be executed for each geological object before an official release to the object library can be made. The model review concerns deliveries of geological models to the model database.

The review process for object and model review is largely the same, with a completion in two steps: (1) a self-review before delivery, and (2) a peer review after delivery, but before release. A simplified flowchart of the two review processes is presented in Figure A5-1a.

Each review step is based on asking several questions and each process contains the same questions for both self- and peer review. All questions in each review shall be considered. If the answer is not affirmative, further explanation is required. The self-review is intended as an initial cleaning step. The approval and final release of an object or model is carried out by a peer review. Affirmative answers to the peer review questions result in approval (i.e. "YES" in Figure A5-1a), whereas deficiencies of the object or model need to be explained and evaluated before approval can be made in the peer review.

An appropriate organisation is necessary to efficiently execute the review process. The site geology team during construction of the repository is proposed to consist of (a) a site geologist responsible for all geological investigations and modelling carried out at the site and (b) separate (but overlapping) groups of mapping and modelling geologists (Figure A5-1b). The site geologist and the modelling geologists are expected to possess the geological knowledge and site understanding required for a total review. Based on this, the review is organised as follows:

- Self-review – carried out by modelling geologist 1, preferably the person that modelled the object or compiled the model.
- Peer review – carried out by the Site geologist with support from modelling geologist 2.

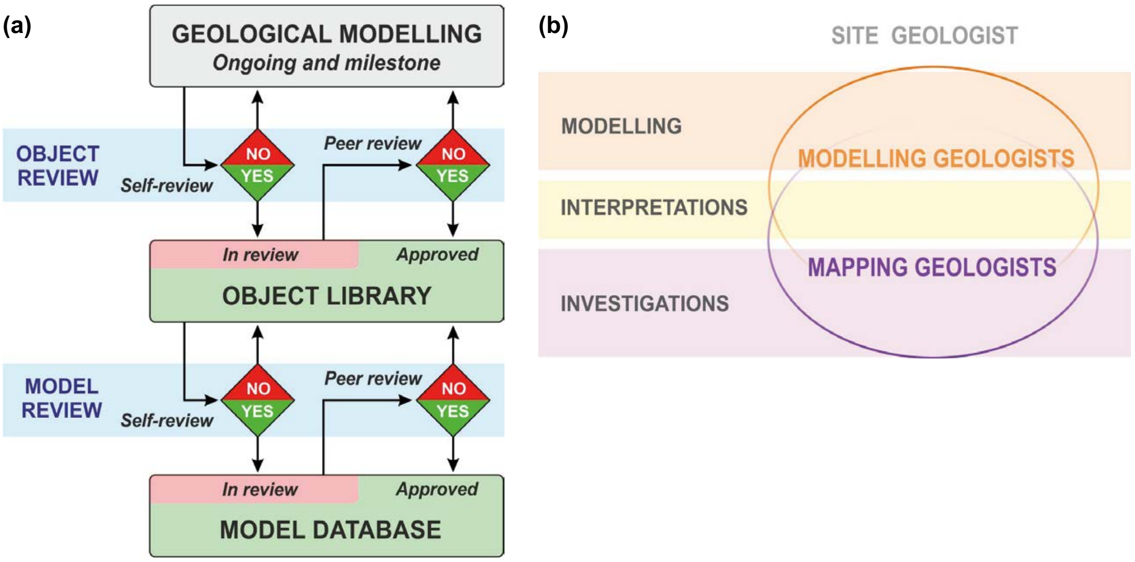


Figure A5-1. *(a) Flowchart for reviewing individual objects and geological models. (b) Proposed site organisation and main functions of the geology team.*

The review forms for both self- and peer review shall include the following administrative details:

- Geological object (or model) name.
- Name of object creator/editor.
- Name of reviewer(s).
- Date of review.
- Constraints of the review (with an explanation of what is reviewed).
- Reviewed object (or model) version.
- Reviewed object description version.

A5.2 Questions for object review

To ensure a consistent review of individual objects during the continuous (ongoing) modelling, several standard questions have been formulated. The topics follows largely the headings of the property tables of Appendix 4 with full details presented in Table A5-1. The questions are valid for review of both deterministic structures and domains with identical questions for both the self-review and the peer review. Affirmative answers on all 15 questions in both review steps are required for final approval in the object library.

Table A5-1. Review questions regarding individual objects, including both structures and domains.

Review topics	Details	Yes	No	Comment
Naming and version	Is the name of the object correct (and for deformation zones also the designation of main orientation)?			
	Is this the intended version of the uploaded object geometry and the corresponding description?			
Geometry (control of orientation, length/volume, thickness, truncations and intersections)	If applicable, is the updated geometry as expected, compared to prior object version?			
	Does the object intersect the intended engineered objects (tunnels and boreholes) and nothing else?			
	Does the object truncate against the intended objects?			
	Does the actual geometry compare to the automatically supplied geometry data in the object description (cf object library in Figure 5-3)?			
Basis for modelling (comparison between the object geometry and interpretations, e.g. BDZs, TDZs, RUs, lineaments, geophysical reflectors, etc)	Is it geometrically reasonable to use the indicated intercepts?			
	Is it geologically reasonable to use the indicated intercepts in terms of structural orientation, geological character and deformation style/intensity?			
	Is the geological/structural variability among the observation points reasonable?			
	Does it exist other alternative geometries with similar level of confidence?			
Conceptual understanding Evaluation of the modelled object considering (a) the current geological understanding (b) the PCS/PCV classification	Does the geological character of the object support the conceptual understanding at the site?			
	Is there reasonable geometric correspondence with other objects (for example trends, orientation, extent)?			
	Is the PCS/PCV classification of the object evaluated?			
Geological character	Is the geological object description correct and in accordance with the data from individual observation points?			
Confidence estimate	Is the assessment of both object and property confidence levels reasonable?			

A5.3 Questions for Model review

Like the object review, several standard questions have been formulated for review of geological models. The focus for the model review is to cover spatial geometrical relations between objects and the selected model volume. At this stage it is expected that geological and conceptual aspects and confidence estimates have already been reviewed during the foregoing object review and should not be revisited at the model review. An advantage with this approach is that the lead times for model deliveries are kept down, where the more time-consuming object review is completed continuously as an integrated part of the modelling work.

The questions, presented in Table A5-2, are valid for review of both deterministic models of structures and domains with identical questions for both the self-review and the peer review. Affirmative answers on all nine questions in both review steps are required for final approval in the model database.

Table A5-2. Review questions regarding the geological models.

Review topic	Question or explanation	Yes	No	Comment
File format	Is the model delivered in an approved file format for export?			
Model Purpose	Is the model delivery in accordance with specifications from downstream users (for example type and extent of objects)?			
Model volume geometry	Is the model delivered using the approved coordinate system for the Forsmark site (SWEREF99 1800 RH2000)?			
	Are the model volume coordinates specified or included as geometry?			
No. of objects	Are all intended objects inside the model volume included?			
Object names, versions	Are the names of the objects correct (and for deformation zones also the designation of main orientations)?			
	Are these the intended versions of the uploaded object geometries and their corresponding descriptions?			
Geometry	Are the intended object truncations against the model volume correct (i.e. truncated against or not)? For block models (domains), is the model volume filled with objects (e.g. space filling)?			
	By visual comparison, can at least one third of the objects in the exported model file and the original objects in the object library be confirmed to have correct geometries?			

Arkitektkopia AB, Bromma, 2022

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