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A strategy for the model development during site investigations

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Contents

1 Introduction

1.1 Background

The Swedish Nuclear Fuel and Waste Management Company (SKB) is at present conducting site investigations as a preliminary to building an underground nuclear waste disposal facility in Sweden. This report presents a methodology for constructing, visualising and presenting 3-dimensional geological models, based on data from the site investigations. The methodology integrates with the overall workflow of the site investigations, from the collection of raw data to the complete site description, as proposed in several earlier technical reports /e.g. SKB, 2000, 2001a,b/. Further, it is specifically designed for interaction with SICADA – SKB's Site Characterisation Database – and RVS – SKB's Rock Visualisation System. However, the concepts of the methodology, as set out here, are intended to be of more general application and to be of use with any tools capable of handling 3D geometries and parameters. The methodology presented here will be subsequently updated as a feedback from users applying the methodology in various modelling projects.

1.2 Aim and outline of the methodology

The geological site descriptive model is intended to constitute a cornerstone in the understanding of the investigated site and forms a basis for subsequent planning of the repository layout as well as for safety assessment studies (Figure 1-1). The general site investigation programme /SKB, 2001b/ describes the methods and techniques for investigating and evaluating the bedrock. The general programme was not site-specific and is currently being supplemented with more detailed programmes for the different disciplines, as well as site-specific programmes, now that the investigation sites have been chosen. Detailed strategy documents have been and are being developed in those disciplines which are considered to be most important for repository design and safety, namely: geology (this report), rock mechanics /Andersson et al, 2002b/, hydrogeology /Rhén et al, 2003 in press/, hydrogeochemistry /Smellie et al, 2002/, thermal properties /Sundberg, 2003/, transport properties /Berglund and Selroos, 2003 in prep/, and surface ecosystems /Löfgren et al, 2003 in prep/. These documents will describe in detail the different methods which will be used in the site investigations and the characteristics and properties which will be described.

This report is, then, one in a series of strategy documents intended to demonstrate how modelling is to be performed within each discipline. However, it also has a wider purpose, since the geological site descriptive model provides the basic geometrical framework for all the other disciplines. Hence, the wider aim is to present a practical and clear methodology for the analysis and interpretation of input data for use in the construction of the geology-based 3D geometrical model. In addition to the various aspects of modelling described above, the methodology presented here should therefore also provide:

- guidelines and directives on how systematic interpretation and integration of geoscientific data from the different investigation methods should be carried out,
- guidelines on how different geometries should be created in the geological models,

- guidelines on how the assignment of parameters to the different geological units in RVS should be accomplished,
- guidelines on the handling of uncertainty at different points in the interpretation process.

In addition, it should clarify the relation between the geological model and other models used in the processes of site characterisation, repository layout and safety analysis. In particular, integration and transparency should be promoted. The methodology should also be compliant to the toolbox of software used by SKB.

/Munier and Hermanson, 2000, 2001/ have earlier described a methodology for geometrically presenting and administering interpreted deformation zones, and the rock masses between, in a site descriptive model to be used in site investigations. That work, written in Swedish, has for practical purposes been partly incorporated into the present report. However, slight departures from the methodology proposed there have been necessary, partly due to experiences gained in the Laxemar project, in which the methodology was applied /Andersson et al, 2002a/, and partly due to advances in the development of the CAD-based RVS tool.

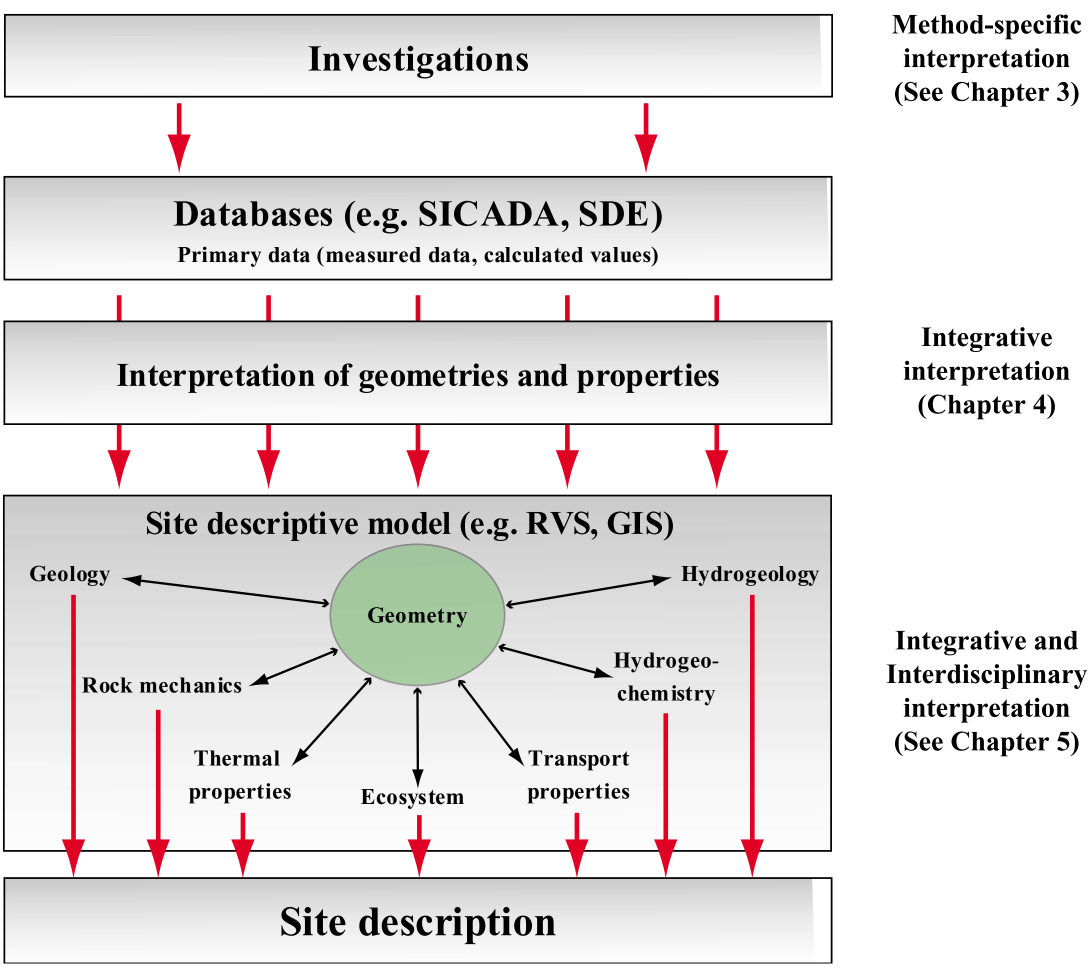

__Figure 1-1.__ Primary data from site investigations are assembled in a database. The data are interpreted and presented in a site descriptive model, which consists of a description of the geometry of the different units in the model and their corresponding properties. The "site description" then consists of the site descriptive model together with the databases on which the model is based. The different types of interpretation defined in Section 1.3, and the chapters in the present report to which they apply, are shown at the right-hand side.

1.3 Levels of interpretation

Geological modelling is based on geological interpretation, which in turn is based on processing and analysis of the raw data acquired during site investigation. In order to clarify the thought processes behind interpretation and, hence, to clarify the methodology of modelling, we will distinguish between three different levels of interpretation, as follows:

Method-specific interpretation (Swedish: *Metodspecifik tolkning*)

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 acquisition, and it is generally based on the application of a particular geological or geophysical technique. This type of interpretation takes place according to standard and generally accepted procedures, and is carried out before the data is stored in SICADA (Site Characterisation Database) and SKB's GIS database SDE (Spatial Data Engine). Method-specific interpretation is, in fact, so routine that it is not mentioned specifically in Figure 1-1 (upper box, marked "Investigations"). An example would be reflection seismic profiles which are constructed semi-automatically from the vibration data recorded during a seismic survey. The result 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 interpretation, albeit standardised and uncontroversial, has been an integral part of its acquisition.

Integrative interpretation (Swedish: *samtolkning*)

This term will be used for the data processing and interpretation carried out by SKB experts in preparation for geological modelling. Integrative interpretation generally involves combining primary data sets from different methods to reach a synthesis of available data within a particular discipline (e.g. combining the data from geological mapping, topographic lineaments, aeromagnetics, etc, to define deformation zones). 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 3D modelling (in Figure 1-1, third box). Integrative interpretation is a necessary bridge between SICADA/SDE and RVS, and hence it should be regarded as an important part of the modelling. The results of integrative interpretation should not be considered as primary input data, since the acquisition of new data, using perhaps a new method, will result in a revised interpretation.

Interdisciplinary interpretation (Swedish: *Ämnesövergripande tolkning*)

This term is used for the type of interpretation requiring interaction and consensus among the different disciplines. This is the main activity once the 3D geological modelling and the use of the results by the different disciplines is under way. In the main box in Figure 1-1, "geometry" is name given to the basic geometrical-geological model in RVS, whilst the different interactions between the disciplines implied in the term "interdisciplinary interpretation" are represented by the arrows (which give only a greatly simplified view of the complex process they are intended to represent).

1.4 Structure of present report

The present report is structured to take account of the different levels of interpretation, outlined above. After a short clarification of the main terms which will be used in the report (Chapter 0), the first of the three main chapters (Chapter 3) outlines the data requirements for 3D geological modelling, together with the main investigation methods (which are detailed in Appendix A1) and the degree of method-specific interpretation in each. This chapter concerns the production of the primary data sets which are stored in SICADA or SDE, which will be later used in the modelling process. The second of the main chapters (Chapter 4) concerns the combination of some of the primary data sets to provide a useable input into the 3D model, with the main emphasis on the process of integrative interpretation. There are two aspects which are particularly important in this context, the analysis and synthesis of geoscientific cartographic data (Section 4.1) and single borehole data (Section 4.2). The third main chapter (Chapter 5) presents the central theme of the report, 3D geological modelling and the process of interdisciplinary interpretation which this involves. In a final chapter (Chapter 6), the treatment of uncertainty and confidence will be discussed in relation to the proposed modelling procedures.

2 Terminology

Within a multidisciplinary project, a uniform and clear nomenclature is essential to avoid misunderstanding and to promote comprehension of the studied site. Previous experience within SKB has shown that terms with seemingly obvious meanings can be understood quite differently, depending upon scientific discipline, academic background, nationality and professional experience. For this reason, we summarise here the meaning of some general terms commonly used within SKB in connection with the present site investigations, together with explanations of some terms used specifically in connection with the methodology presented in this report.

Deformation zone (Swedish: *deformationszon*)

The term *deformation zone* is used to designate an essentially 2-dimensional structure (a sub-planar structure with a small thickness relative to its lateral extent) in which deformation has been concentrated (or is being concentrated, in the case of active faults). If there is sufficient geological information, deformation zones can be further qualified as brittle, ductile or composite. The term *composite* is applied to deformation zones which show evidence of both brittle and ductile deformation. Composite deformation zones commonly show evidence of *brittle reactivation*, i.e. brittle deformation of already ductilely deformed rocks along the same zone, but this is not necessarily the case and has to be demonstrated. The commonly used term "fracture zone" can be used to denote a *brittle deformation zone* or the *brittle part* of a composite deformation zone. The commonly used term "ductile shear zone" can be used to denote a *ductile deformation zone* or the *ductile part* of the composite deformation zone. The aim in modelling is to be able to qualify all significant deformation zones in the model, as more and more information from the site investigations becomes available. Figure 2-1 shows how deformation zones can be subdivided into smaller components.

Discipline (Swedish: *Ämnesområde*, literally "subject area")

In many recent SKB reports, the term *discipline* has been used specifically for the seven research areas defined for the purpose of the present site investigations. The disciplines are: geology, rock mechanics, thermal properties, ecosystem, transport properties, hydrogeochemistry, and hydrogeology (see Figure 1-1). This usage is retained in the present report.

Domain (Swedish: *Domän*)

Units, for example rock units, can often be grouped together into domains with reference to a particular property. A geological *domain* in the bedrock can be composed of one or several rock units with similar characteristics with respect to a particular property. Two rocks, e.g. granite and gabbro, are considered as two separate domains with respect to physical properties, whereas two granitic rocks, e.g. granodiorite and tonalite, can be combined into a single domain, since their physical properties are similar. Units with similar hydraulic properties can be grouped into a hydraulic domain, irrespective of differences in other physical properties. The term is used primarily in the model description and for conceptual models, and is dependent on the aim of the modelling (see section: **Units and Domains**, below).

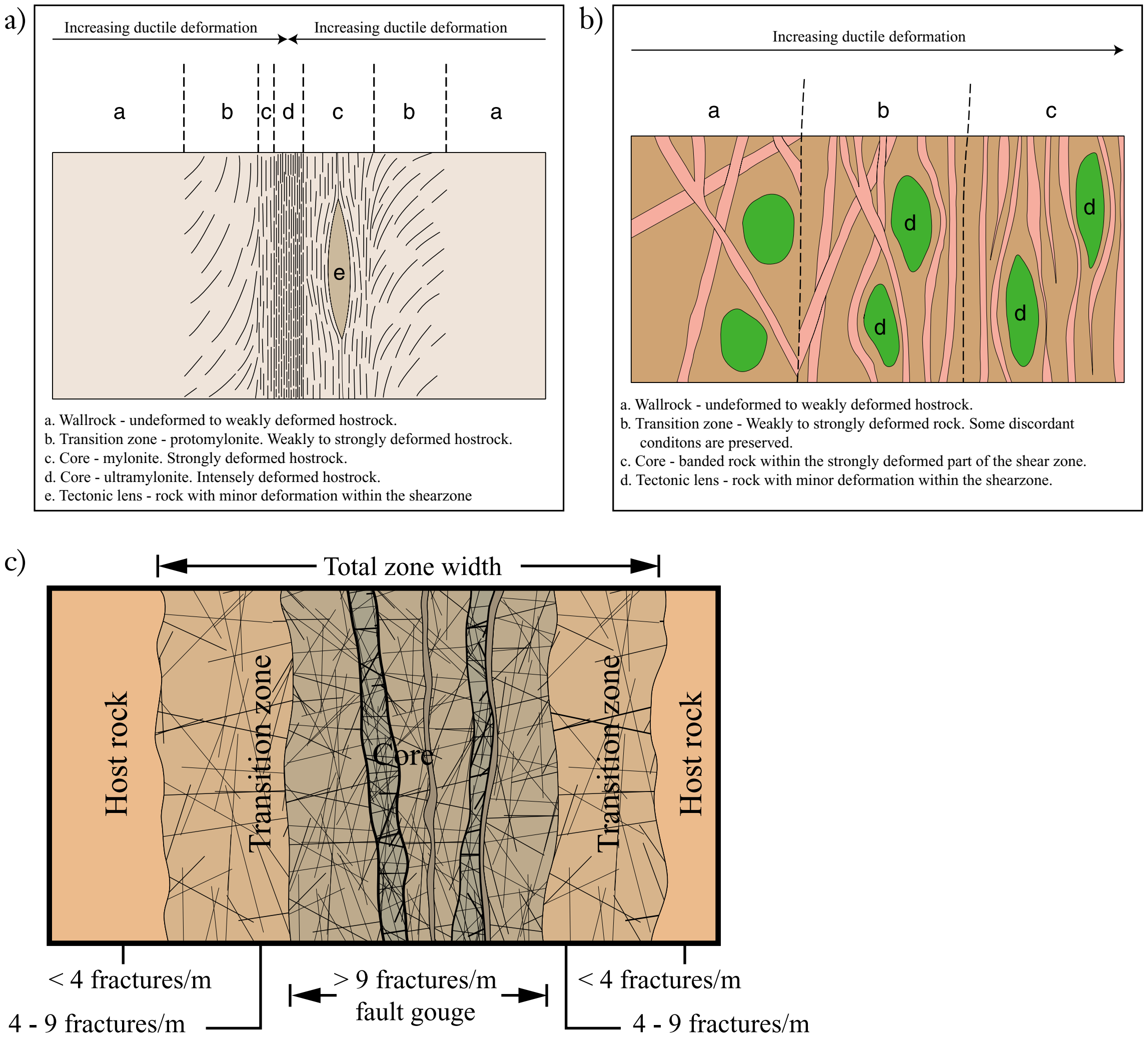

Figure 2-1. *(a) Schematic example of a ductile shear zone (1). Homogeneous rock which is deformed under low to intermediate grade metamorphic conditions. The increasing degree of deformation is reflected in the formation of protomylonite, mylonite and ultramylonite. The zone may contain less deformed rock volumes, often shaped as lenses. The example shows sinistral shear. (b) Schematic example of a ductile shear zone (2). Heterogeneous rock which is deformed under low to high grade metamorphic conditions. The host rock consists of e.g. tonalite (brown) intruded by an ultramafic rock (green) and a swarm of granitic dykes (red). (c)Schematic illustration of the structure of a brittle deformation zone.*

Geological model (Swedish: *Geologisk modell*)

This is a commonly used designation for a geoscientific model which shows the geometries of superficial deposits, rock units, deformation zones, etc, together with their characteristic parameters (properties). With regard to the bedrock, which is the main focus of the present report, a geological model consists of a combination of a lithological model and a structural model of a particular area, to which can be added the topography and soil thickness. A model in this usage is a simplified representation of nature, based on a synthesis of the primary data, which is amenable to numerical computations whilst still retaining the essential, first-order natural characteristics.

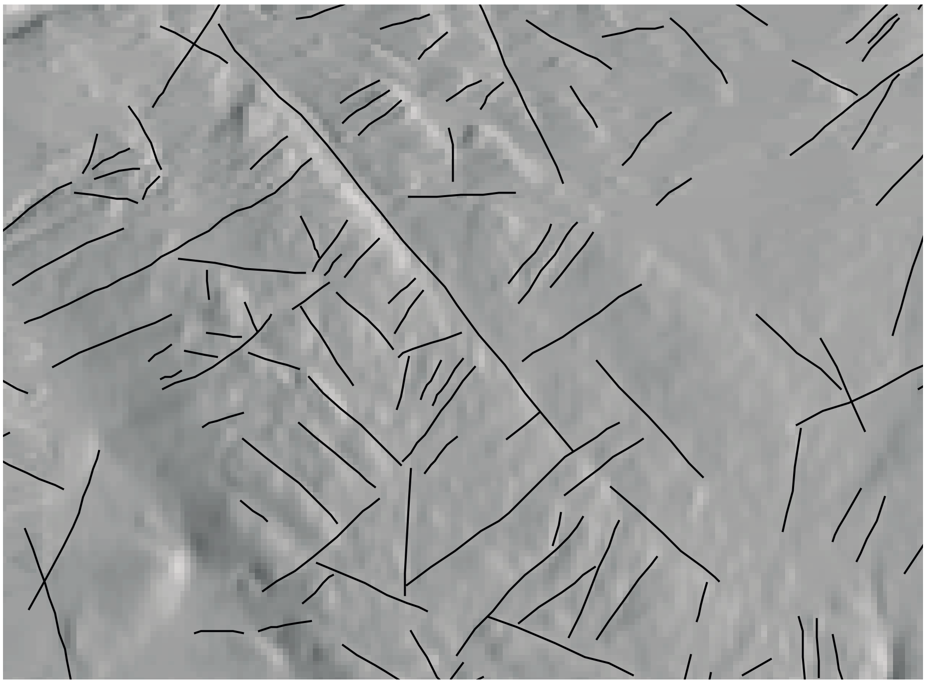

Figure 2-2. *Topographic lineaments interpreted from a DTM*

Lineament (Swedish: *Lineament*)

A *lineament* is a linear anomaly on the Earth's surface, straight or gently curved, which has been interpreted on the basis of a 2-dimensional data set, such as a topographic map, a digital terrain model (DTM), an air photo mosaic, or an aeromagnetic map. A lineament can, but does not necessarily, indicate a geological structure, such as a deformation zone, a dyke rock, or an esker. Lineaments are qualified according to their origin (i.e. the method or data base which led to their definition), for instance, topographic lineaments, magnetic lineaments, etc.

Model scale (Swedish: *Modellskala*)

Within SKB, the following terms are used to denote different model scales:

- *regional scale* (horizontal model area > 10 km^2),
- *local scale* (horizontal model area 5–10 km^2).

Parameter (Swedish: *Parameter*)

The term "parameter" is used in a very wide sense in SKB reports (see, for instance /Andersson et al, 1998/ and all subsequent site investigation and evaluation studies). All characteristics, features and properties are included in the term, whether they are measurable and quantifiable (normal English usage) or not. However, with regard to the modelling described in this report, the use of the term almost always implies a measurable and quantifiable characteristic, and the term "parameterisation" is used for the assignment of numerical values of a particular property to the different objects in the model.

Site description (Swedish: *Platsbeskrivning*)

A site description is composed of 2D (GIS) and 3D (RVS) models, connected to databases containing data from site investigations (SICADA, SDE), and a written description (Technical Report), which explains in detail the modelling process, indicates the sources of error, gives estimates of the uncertainties, and makes recommendations for further investigations. The intended use of the site description is for the planning of further investigations, for the design of the repository, and for the underpinning of the safety assessment.

Soil (Swedish: *Jord*)

The term *soil* is, in this report, used in the engineering geological sense, i.e. as synonymous with "regolith", which is defined as follows /Bates and Jackson, 1987/: "A general term for the layer of fragmental and unconsolidated rock material, whether residual or transported, and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock. It includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess and eolian deposits, vegetal accumulations, and soil (*solum*)…". The term soil, as used here, thus constitutes a subgroup to the more general term "unconsolidated deposits" which in addition to these terrestrial deposits, includes also marine and lacustrine deposits.

Unit (Swedish: *Enhet*)

A *unit* is the smallest, undivided volume in a 3D geological model. Depending on its properties and intended use, the following qualifiers may be applied: rock unit (lithological unit) and structural unit (e.g. within a deformation zone) in bedrock models (as in this report), and soil unit, water unit, and air unit in more complex models (ones including superficial deposits, marine areas, underground excavations, etc). The term is used in this sense primarily in (geometric) modelling work.

Units and Domains

For the methodology of 3D modelling of bedrock, it is important to clearly distinguish between units and domains (see definitions above). This can be illustrated with a series of schematic diagrams showing hypothetical maps of a bedrock area (Figure 2-3). The starting point is an area with a series of igneous intrusions, cut through in part of the area by swarms of veins (Figure 2-3a). Four different rock types give, in the first instance, three rock units (units 1–3). Units 1 and 2 have similar physical properties and constitute one domain (Figure 2-3b, domain 1). Unit 3 (gabbro) has properties which diverge from those of the granitoid units and forms therefore a separate domain (Figure 2-3b, domain 2). One area (parts of two rock units) shows a high concentration of fine-grained granitic veins. Because of the strong lithological heterogeneity of the intruded rocks, yet another unit, unit 5, is distinguished. This area constitutes a separate domain (Figure 2-3b, domain 3) because of divergent bulk properties in relation to domain 1 (granitoid, without veins).

Figure 2-3c shows the same geological map, now intersected by a deformation zone. The deformation zone intersects rock units 1, 2 and 3 and creates a series of new rock units (units 6–7), as well as subdividing some units into two parts, which become separate rock unit (8,9). Because of its divergent properties, the deformation zone becomes a separate domain, independent of the rock types which occur within the zone (Figure 2-3c, domain 4). However, any subdivision into domains depends on the aim of the modelling. If the purpose of the subdivision into domains is to construct a rock mechanical model, it may be appropriate to distinguish only two domains, the deformation zone and its surroundings (Figure 2-3d, domains 1 and 2), based on the different rock mass properties from a rock engineering point of view. Similarly, if the modelling is for groundwater flow modelling, a further subdivision may be appropriate, since the veined area will probably have different hydrogeological properties (e.g. bulk permeability) to the unveined areas outside the deformation zone (Figure 2-3e, domain 2).

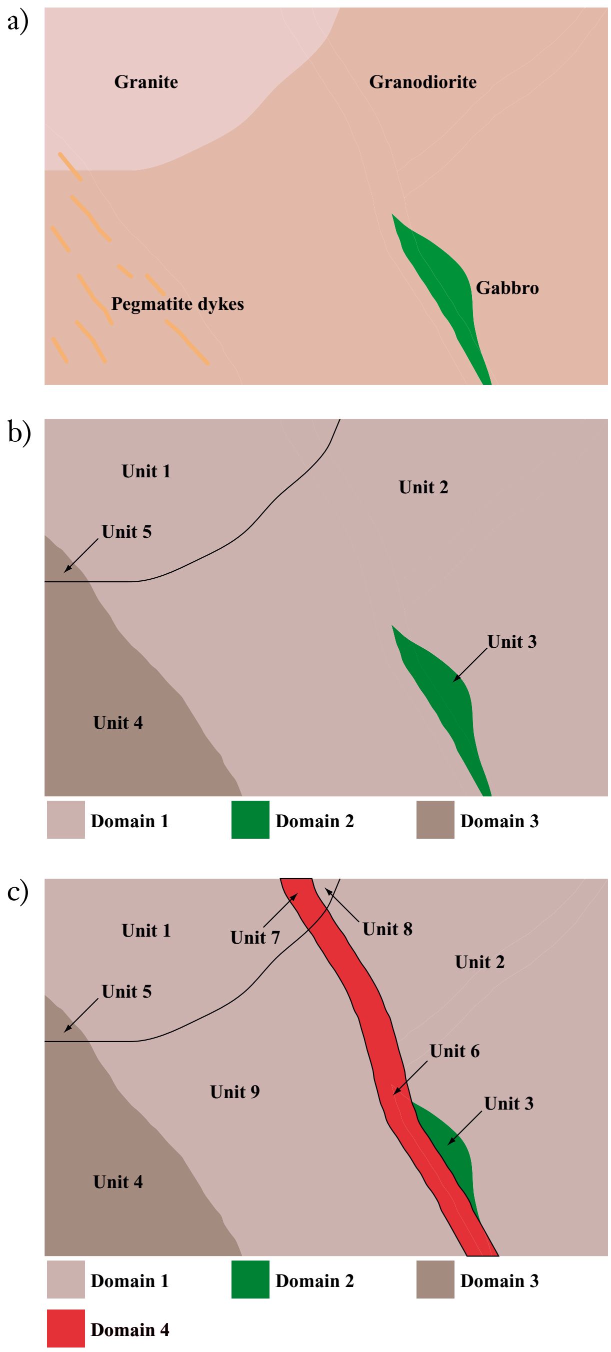

Figure 2-3. *Illustration of the concepts of units and domains (for explanation, see text). (a) A hypothetical geological map showing the distribution of a number of rock units and an area characterised by swarms of granitic veins. (b) The same map subdivided into3 domains according to the physical properties and heterogeneity of the bedrock. (c) The bedrock in "a" is intersected by a deformation zone, creating 5 additional rock units.*

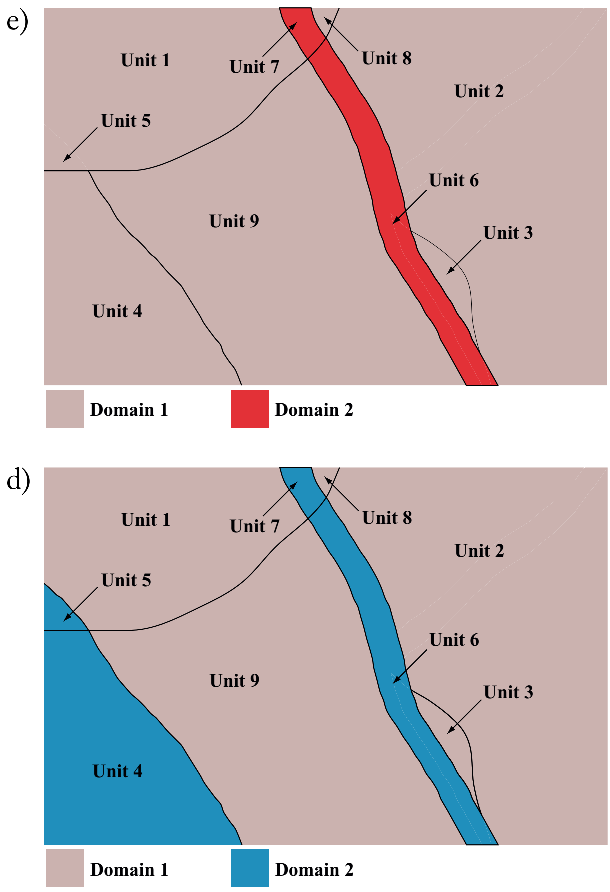

Figure 2-3. *cont.*
(d) From a rock mechanical point of view (e.g. rock engineering properties of the rock mass), the bedrock in "c" can be subdivided into 2 domains, as shown. (e) From a hydrogeological point of view (e.g. bulk permeability), the bedrock in "c" can also be subdivided into 2 domains, only partly coincident with those in "d".

3 Site investigation methods and acquisition of primary data for geological modelling

In this chapter, we briefly present the main geophysical and geological methods which will provide the primary database, accompanied by tables focussed on the type and extent of *method-specific interpretation*. The idea is to use the outcome of the listed methods and processes as building blocks for the model. The process of integrating these building blocks into a site descriptive model is outlined in Chapters 4 and 5. Here, we briefly describe various building blocks that may be used as input to the geological site descriptive model, focussed primarily on the bedrock.

Descriptions of the geophysical and geological methods used in site investigations 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 interpretation is to be carried out. Method descriptions and their handling constitute an important component of the QA system used at SKB. They have been written to ensure that repetitive tasks are performed in a similar way during site investigations, that the methods are applied in a similar way in the two sites, and that the delivered data is quality assured. Each method description is given an MD number according to SKB's internal classification system (for explanation, see Appendix A1). A list of the main methods which provide data for the geological site descriptive model in the present site investigations, together with their MD numbers and a brief outline of each method and its uses, is given in Appendix A1.

The briefness of the descriptions presented in Appendix A1 is, however, not justified with respect to the contents of the method descriptions, and in particular their sub-references, or to the expertise of those that eventually will carry out the investigations. It is not possible, within this document, to fully express the complexity of the processing and method-specific interpretation that forms the cornerstone of many of the listed methods. For instance, one of the items is "bedrock mapping", which is carried out according to standard procedures adopted by the Geological Survey of Sweden. We thus here distil into a few sentences about a century of geological know-how, expertise and scientific excellence. Hence, the descriptions in Appendix A1 should merely be regarded as thumbnail sketches, for orientation in the present report.

In the following, the methods have been classified into two groups. The first group contains *individual methods* (Section 3.1, Table 3-1), that is, methods which are recognised in the scientific community as being self-contained, based on a particular physical and/or chemical technique and subject to method-specific processing which is now standardised and internationally accepted. Some methods included may fit this definition less strictly than others, but nevertheless are based on generally recognised procedures and techniques (e.g. the "bedrock mapping" mentioned above). The second group has been called *combined methods* (Section 3.2). This is a heterogeneous group, covering various aspects of the combination of different methods. Firstly, it is used for groups of individual methods which are always carried out in combination (here represented by airborne geophysics, Section 3.2.1, and geophysical borehole logging, Section 3.2.2). The data acquisition and initial processing is carried out by a single contractor using standardised methods, but the number of methods used may vary from survey to survey. Secondly, it includes standardised procedures in which the data from several different methods are combined, using semi-automatic, statistical processing to calculate a single parameter, which is then used in the subsequent modelling as primary input data (here represented by the Fracture Zone Index, Section 3.2.3). Finally, we include the more extensive processing and analysis of fracture data which is necessary for developing the input data for Discrete Fracture Network modelling, which will eventually be an integral part of geological modelling procedures (Section 3.2.4, Appendix A2).

3.1 Individual methods

The individual methods and techniques which will be used in the site investigations to acquire the primary data needed to carry out 3D geological modelling of the bedrock are listed in Table 3-1, and brief summaries are given in Appendix A1. The first column in Table 3-1 gives the method name and the corresponding MD (Method Description) number in the SKB QA system. These can be obtained from SKB upon request. In the second column, brief comments are added to each method on the degree and type of method-specific interpretation. In the 5 remaining columns, crosses indicate the main area(s) of application of the primary data, subdivided into usefulness for 2D modelling (interpretative maps of features at the Earth's surface) and usefulness for 3D modelling (reconstructions of subsurface relationships). The crosses only give general indications, since all primary data will be continuously reassessed in the light of their possible contribution to other activities in the course of site descriptive modelling.

3.2 Combined methods

As mentioned above, some methods are more complicated than those of the previous section, and do not fit easily into the summary table (Table 3-1). The reasons for this are diverse, making it necessary to treat them in more detail. The "combined methods" which are relevant to the process of 3D geological modelling in crystalline bedrock are listed in Table 3-2, and described in the following sections (Sections 3.2.1 to 3.2.4).

Table 3-1. Summary of the main geological and geophysical methods which will be used as a basis for 3D geological modelling in SKB's site investigations (see also Appendix A1).

Method (MD number) – see Appendix A1 for brief method descriptions	Comments on method-specific interpretation	Useful for 2D modelling modelling (synthesis of surface data)			Useful for 3D modelling (synthesis of subsurface data)	
		Linea-ment	Soil	Bed-rock	Struc-ture	Litho-logy
Individual methods						
1 Topographical data (MD 120.001)	Digital terrain analysis combined with satellite imagery and aerial photo interpretation, to produce a topographic lineament map	X				
2 Soil mapping (MD 131.001)	Mapping combines data from geomorphology, shallow bore-holes, trenches, gravel pits, etc, to produce soil maps and stratigraphic columns		X			
3 Neotectonics (MD 133.001)	Synthesis of data on very young (Quaternary, post-glacial) fault movements – not really a "method", requires integrative interpretation		X	X		
4 Mapping of bedrock outcrops (part of bedrock mapping, MD 132.001)	Geol. mapping of bedrock outcrops, acc. to standard SGU procedures, to produce an "outcrop map" (for "bedrock map", see Chapter 4)			X	X	X
5 Fracture mapping (MD132.003)	Outcrop mapping of fractures/ fract. systems, using standard methods (see Section 3.2.4 and Appendix A2)			X	X	
6 Petrographic analysis (MD 160.001)	Standard thin-section (polarising microscope) and powder (X-ray diffraction) methods			X		X
7 Radiometric age determination (MD 132.002)	Spectrum of isotopic methods, depending on the problem to be solved – standard analytical procedures, but "age" often controversial			X		X
8 Analysis of drill cuttings (MD 142.001)	Visual/microscopic evaluation of rock fragments in drilling fluid from percussion drilling – simple method, in support of item 21			X		X
9 Drillcore mapping ("Boremap", MD 143.006)	Systematic structural and petro-graphic description of rock cores, incl. sample analysis (see items 6 and 7), preferably carried out together with item 21, below			X	X	X
10 Petrophysics (MD 230.001)	Measurement of physical properties of rocks (standard methods) in outcrop and on samples	X		X	X	X
11 Marine geology (MD 260.001)	Synthesis of data on seafloor and sub-seafloor conditions from marine studies (acoustic geophysics, sediment sampling, etc)	X	X			

Method (MD number) – see Appendix A1 for brief method descriptions	Comments on method-specific interpretation	Useful for 2D modelling modelling (synthesis of surface data)			Useful for 3D modelling (synthesis of subsurface data)	
		Linea-ment	Soil	Bed-rock	Struc-ture	Litho-logy
12 Reflection seismic profiling (MD 241.004)	Standard surface-based method of subsurface exploration, with processing optimised for crystalline rocks (together with item 13)				X	X
13 VSP (Vertical Seismic Profiling) (MD 243.003)	Standard borehole-based method of sub-surface exploration, with processing optimised for crystalline rocks (together with item 12)				X	
14 Resistivity measurements (MD 212.005)	Standard surface-based method of subsurface exploration	X	X	X	X	X
15 Slingram (MD 212.007)	Standard surface-based method of subsurface exploration (electro-magnetic measurement technique)	X			X	
16 VLF (Very Low Frequency) (MD 212.006)	Standard surface-based method of subsurface exploration (electro-magnetic measurement technique)	X			X	
17 Refraction seismics (MD 242.001)	Standard surface-based method of subsurface exploration, with processing optimised for crystal-line rocks (see items 12 and 13)	X	X		X	
18 Ground Penetrating Radar GPR (MD 251.003)	Standard surface-based method for subsurface exploration of soil (electro-magnetic measurement technique)		X			
19 Gravimetry (MD 212.003)	Systematic measurement of gravitational field at the surface – data acquisition/processing standard, intepretation often controversial			X		X
20 Magnetometry (MD 212.004)	Systematic measurement of the magnetic field at the surface – standard method of mapping distribution of magnetic minerals	X		X	X	
21 Borehole-wall imagery (MD 222.006)	TV imagery of borehole wall (BIPS, OPTV, and similar instrumentation), preferably used in conjunction with rock cores (item 9)				X	X
22 Borehole radar (MD 252.020)	Standard surface-based method of subsurface exploration, with processing optimised for crystalline rocks				X	X

Table 3-2. Summary of some combined geological and geophysical methods which will be used as a basis for 3D geological modelling in SKB's site investigations (for explanation, see text).

Method	Comments on method-specific interpretation	Useful for 2D modelling modelling (synthesis of surface data)			Useful for 3D modelling (synthesis of subsurface data)	
		Linea-ment	Soil	Bed-rock	Struc-ture	Litho-logy
Combined methods						
A Airborne geophysics (MD 211.002 and 211.003)	See Section 3.2.1 and Table 3-3	X	X	X	X	X
B Geophysical borehole logging (MD 221.002, MD 221.003)	See Section 3.2.2 and Table 3-4				X	X
C Fract. Zone Index (FZI) (MD 810.003)	See Section 3.2.3				X	
D DFN analysis (this report, Appendix A2)	See Section 3.2.4 and Appendix A2				X	

3.2.1 Airborne geophysics

Airborne geophysical surveys by helicopter (SKB method descriptions MD 211.002 and 211.003) are carried out to investigate the physical properties and structure of the bedrock and the overlying soils (see Table 3-3). These methods also yield results which contribute towards subdividing and classifying the soil and the bedrock into various sediment and rock types, as well as towards detecting and orienting structures, lineaments and deformation zones.

The different methods provide information from different depth intervals in the geosphere. In general, the resolution is greatest near the surface and decreases with depth. To generalise somewhat, the airborne geophysical systems which are available on the market today yield information from the following depth intervals, in the types of geological milieu which are being worked on by SKB:

- Gamma-radiation spectrometry elucidates conditions at the surface.
- EM gives information from the surface down to between 50 and 150 m.
- Magnetometry can give an impression of the distribution of rock types down to several hundred metres of depth.

Table 3-3. Measurement methods in airborne geophysics, and the significance of the different types of information for modelling lithologies and structures in the bedrock and soil distribution.

Method	Lithological model	Structural model	Soil cover	Other information
Magnetometry (MD 212.004)	Distribution of magnetic minerals (chiefly magnetite) provides information on rock distribution in 3D down to few hundred meters depth, due to rock-specific variations in magnetic mineral content.	Magnetic minerals can be altered in fracture zones and lose magnetic susceptibility. Magnetic minerals can be arranged in patterns which reveal deformation structures.	Normally no significant information.	
Electromagnetic measurements MD 212.008)	Electrically conducting rocks usually contain graphite or sulphide minerals (often pyrrhotite) and can therefore be mapped with the aid of EM. Such rocks occur normally, in the bedrock, only outside the areas which SKB has prioritised for site investigations.	Fracture zones are often electrically conductive due to their content of water and clay minerals. If the surrounding rocks have a lower conductance, such zones can be mapped with the aid of EM, provided that their conductivity is sufficient.	EM can provide a certain amount of information on thickness and type of soil. Different soil types show different conductivities, but their conductivities are generally higher than those of the bedrock, in the case of the rock types which are typical for SKB's sites (granite and gneiss).	Can give some information on water depth offshore.
Gamma-radiation spectrometry (MD 212.002)	The fact that different rock types contain different amounts of K, U and Th makes spectrometry a possible mapping tool. Soil, however, has a shielding effect, and can make such mapping impossible if the degree of exposure is low.	Normally no significant information, except indirectly by indicating rock distribution.	Normally little significant information, although in some cases it has proved useful for identifying certain types of soil.	Reflects relative degrees of ground humidity.

3.2.2 Geophysical borehole logging

For SKB's site investigations, it is of great importance to be able to localise fractures and to evaluate the distribution of rock types and fractured rock in boreholes. For this purpose, conventional geophysical borehole logging (often called "wireline logging") is an important technique (SKB method description MD 221.002). Geophysical borehole logs provide the basis for a "pseudo-geological" mapping of the borehole (see below). With different tools, a number of physical parameters are determined, and detailed study of the logged parameters can, in many cases, differentiate between different rocks and different types of alteration. Usually, one parameter is insufficient for this and a combination of the logs of several parameters is necessary. Borehole sections of fractured rock commonly give anomalous measurements, enabling them to be identified and located. Geophysical logging can be carried out in both cored and percussion-drilled boreholes.

For geological single hole interpretation (Section 4.2), geophysical logs are not used in their primary form. Instead, transformed and interpreted versions are used, in which the results of several different logs have been integrated and transformed into so-called "pseudo-logs" ("pseudo-lithology logs" and "pseudo-fracture logs") The methodology describing the processes of creating these logs is currently (march, 2003) being developed. *Pseudo-lithology logs* show the classification of rocks, based on the integrative interpretation of the natural gamma, gamma-gamma, and magnetic susceptibility logs. For this classification, determinations of the petrophysical characteristics of rocks are used, together with analysis of drill cuttings. *Pseudo-fracture logs* show where, along the borehole, a number of geophysical logs have identified fractures or sections with fractured rock. The logs used are the caliper log, the sonic log and a number of different resistivity logs (SPR, normal resistivity, focussed resistivity, fluid resistivity).

Logging is often carried out by combining several techniques, and probes of several types are joined for more effective work. A compilation of the most common techniques is given in Table 3-4.

Table 3-4. Compilation of the main geophysical borehole logging techniques which will be used in SKB's site investigations, and their application (Y = Yes, N = No).

Technique	Measured parameter	Fracture detection (Y/N)	Lithology determin-ation (Y/N)	Comments
Gamma ray logging (MD 212.002)	Intensity of natural gamma radiation	N	Y	
Gamma-gamma or density logging (MD 212.002)	Density	(Y)	Y	Can be used as input data when interpreting sonic logs
Resistivity logging (MD 212.002)	Normal resistivity	Y	(Y)	Lithology determination is only possible if the rocks have sufficiently different primary porosity or if graphite or sulphides occur
"	Lateral resistivity	Y	(Y)	See above
"	SPR	Y	N	See above
"	Focussed resistivity	Y	N	See above
"	SP	(Y)	N	Bi-product of resistivity measurement
Susceptibility logging (MD 212.002)	Magnetic susceptibility	(Y)	Y	
Sonic or acoustic logging (MD 212.002)	P-wave velocity	Y	(Y)	
"	S-wave velocity	Y	(Y)	Can be used together with P-wave velocity and density to calculate elastic parameters
Fluid resistivity logging (MD 212.002)	Fluid resistivity	(Y)	N	Used for correcting resistivity logs. Yields information on inflow and outflow of fluids in the borehole
Temperature logging (MD 212.002)	Temperature	(Y)	N	Used for calculating salinity from the fluid resistivity. Yields information on inflow and outflow of fluids in the borehole
Caliper logging (MD 212.002)	Borehole diameter	Y	N	Data necessary for correction of the other logs

3.2.3 Fracture Zone Index FZI

FZI is a classification of the rock mass encountered in a borehole with respect to rock quality, and is carried out according to SKB method description MD 810.003. The purpose of the method is to aid in identifying potential fracture zones in a borehole and it thus constitutes a component of the single hole interpretation (MD 810.003). The FZI method uses multi-variant statistics to describe and classify the rock mass into:

- Wall rock (normally fractured rock) – FZI < 0,5
- Transition zone – FZI 0,5–1,5
- Possible fracture zone – FZI > 1,5

The primary input data for the calculation consist of fracture frequency, borehole radar reflectors and geophysical borehole logging data. Of the geophysical logs, caliper, sonic and resistivity logs gives the most significant contribution (see Table 3-4).

The process of converting these different data sets to a single parameter (FZI) is based on complex statistical and modelling procedures (Principle Component Analysis), as described in method description MD 810.003.

3.2.4 Discrete Fracture Network (DFN) analysis

DFN analysis is a standardised procedure for statistically analysing fracture data, and the background and methods, are described in Appendix A2.

The possibilities of fixing the geometry and properties of individual fractures in a large-scale model deterministically are extremely limited. Hence, a statistical treatment is used to describe fracture systems in rock bodies. The fracturing is described with the help of so-called DFN (Discrete Fracture Network) parameters which define the geometries, directions and spatial distribution of the fractures, as well as other characteristics, such as mineralogy and transmissivity. RVS models, and their inherent DFN parameters, can afterwards be used, in DFN codes specially developed for that purpose, for understanding how the fractures influence stability, and groundwater flow and transport in and through the rock mass.

Information from outcrops and boreholes provide the basic data for defining the DFN parameters (Table 3-1, items 5, 9 and 21). These data, however, must go through an extensive processing before they can, in a correct way, simulate the properties of the natural fracture network. This processing, as it will be implemented in SKB's site investigations, is outlined in Appendix A2.

3.3 Summary

The aim of this chapter was to give a brief overview of the different methods and techniques which will be used in SKB's site investigations to provide the data base for the geological site descriptive model, and to outline the degree of method-specific interpretation which they involve. The methods outlined produce the primary data base on which the site descriptive models will be built. The rest of this report concerns the methodology of building a geological site descriptive model, using this primary data base. Here, we enter the realm of "integrative interpretation", the problem of integrating different primary data sets, produced by different methods, to create a unified model.

4 Integrative interpretation: preparation of geoscientific maps and single borehole interpretations

Much of the primary data stored in SICADA, the results of the methods and method-specific processing and interpretation stored in GIS (outlined in Chapter 3), need to be integrated and synthesised before they can be used for modelling in RVS. This applies particularly to the data relevant to building the basic geometrical framework of the site descriptive model, i.e. to the 3D system of lithological and structural features which are deterministic at the scale of the model. This process of integration and synthesis is essentially directed towards combining the results of different methods within the same discipline, to give the best estimate of the position, orientation, thickness, etc, of a particular feature within the model volume, to represent the bedrock underlying the investigated site. This type of integration and synthesis is here called "integrative interpretation" (Swedish: *samtolkning*, see Chapter 0), and it can be thought of as a preparatory stage of the modelling process described in Chapter 5.

In the present site investigations, two activities of this preparatory type are of central significance:

1. preparation of geologic maps – essentially 2D cartographic models of bedrock conditions at the Earth's surface, above the site and its surroundings,

2. preparation of geologic single hole interpretations – essentially 1D models of bedrock conditions along, and in the immediate surroundings of, each individual borehole at the site.

How these activities will be carried out in SKB's site investigations will be outlined in Sections 4.1 and 4.2, below. They are based more on expert judgement and experience than on automatic or semi-automatic processing of primary data sets. The results provide the basic controls on the modelling, i.e. an upper control surface to the model volume, and a series of internal control lines within the model volume, respectively. All 3D arrangements of geological features within the model volume, and all alternatives and revisions, have to honour the control points provided by this basic configuration.

The third preparatory activity which will be outlined in this chapter (Section 4.3) concerns the process of filling the space between the control points provided by geoscientific surface maps and single borehole interpretations, within the model volume. Here, we simply outline some main elements of the process, which we will call multi-hole interpretation, a term which here includes such activities crosshole, multi-hole and hole-to-surface correlation, different types of geophysical modelling, predictive structural geology, between-hole hydrogeological testing, and the like.

4.1 Preparation of geoscientific maps

The first task of integrative interpretation is to prepare a 2D lithological and structural model of the Earth's surface at the scale appropriate to the aim of the modelling. The first step is to integrate the different method specific interpretations of "remote" data – satellite imagery, aerial photography, topographic data, airborne geophysics, and bathymetry – to produce a *lineament map* (Section 4.1.1). In general, this type of method specific interpretations does not provide definitive evidence of the geological significance of the lineaments. Hence, the lineament map itself must be integrated with available structural geological data and ground geophysics, particularly with respect to the degree of certainty with which the lineaments can be considered as the traces of deformation zones (for terminology, see Chapter 0). This second step produces a *deformation zone map* (Section 4.1.2). Finally, the deformation zone map is combined with the results of geologically mapping the rock outcrops throughout the area, and any other information on the lithological make-up of the site, to produce a *bedrock map* (Section 4.1.3). The bedrock map forms the basis of the 2D cartographic model of the upper surface of the model volume, as input to RVS.

4.1.1 Lineament maps

At an early stage in the site investigations, method-specific processing and interpretation of topographic data (digital terrain model, orthophotos, satellite images, etc), airborne geophysics and marine investigations have usually been carried out. These form the basis of, amongst other things, the integrative interpretation of lineaments in the study area, as described in this section. The aim of integrative interpretation in this case is to evaluate and combine the lineaments defined by the different method-specific processing and interpretation procedures to a common lineament map, with a descriptive document.

Process of integration

The integration process is visualised in Figure 4-1. In practice, a greater part of the work is done electronically, mainly in a GIS environment. The work is carried out in the form of a cooperation between a geologist and a geophysicist. Before the work starts, all the information is processed to be presentable in GIS. The products from the method-specific processing and interpretation, as well as any supporting data from the GIS databases, are prepared. These products should provide the following basic data:

- From the topographic data, lineaments and other structures which could indicate possible deformation zones have been identified.
- From the airborne magnetometry, elongate zones in the bedrock with low magnetic susceptibility, or lines of dislocation in the magnetic anomaly patterns, have been identified in map view. In a few instances, modelling has been carried out to give an indication of the dip of the zones.
- From the airborne EM, elongate zones of high electrical conductivity have been identified in map view.
- From the airborne EM or from marine geological studies, elongate depressions in the basement surface in water-covered areas have been mapped.

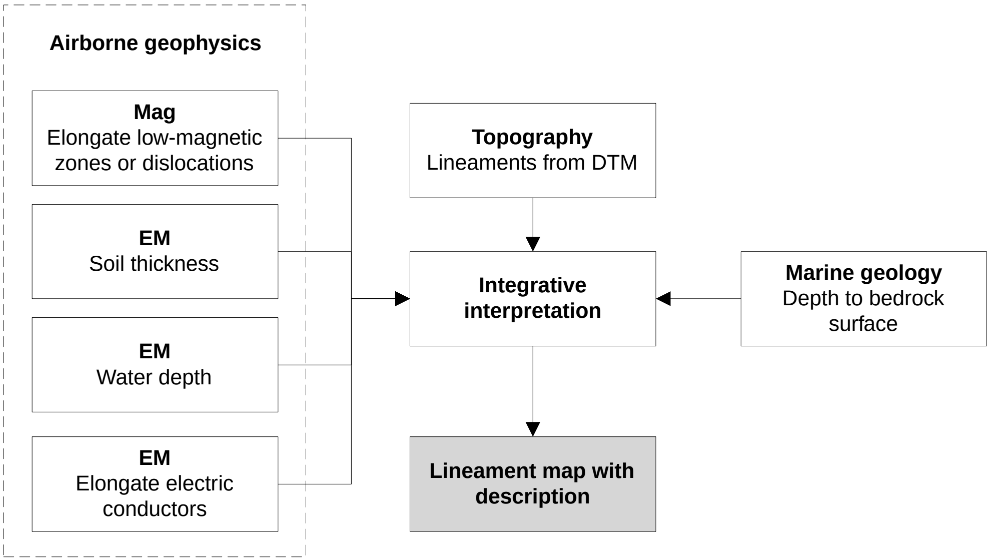

Figure 4-1. *Flow diagram for the integrative interpretation of lineament data, using topographic data, airborne geophysics and marine geology.*

The different maps give a number of different suggestions as to the definition and extent of lineaments. During the process of integrative interpretation, the different suggestions are fused into an integrated lineament map. The work process can be summarised as consisting of:

- comparing the alternative lineament maps with each other,
- modelling the geophysical data, if necessary,
- integrating the different alternatives to a single lineament map, and
- describing the integrated map, pointing out the main inconsistencies between the different alternatives and indicating the reasons for the decisions made.

The result of the integration process is, as indicated, a lineament map (Figure 4-2) with a descriptive document. It is essentially a 2D representation, with some depth information at certain places. The integrated map is stored in SDE and RVS, for later integration with geoscientific surface data, and incorporation in the deformation zone map and bedrock map (see below).

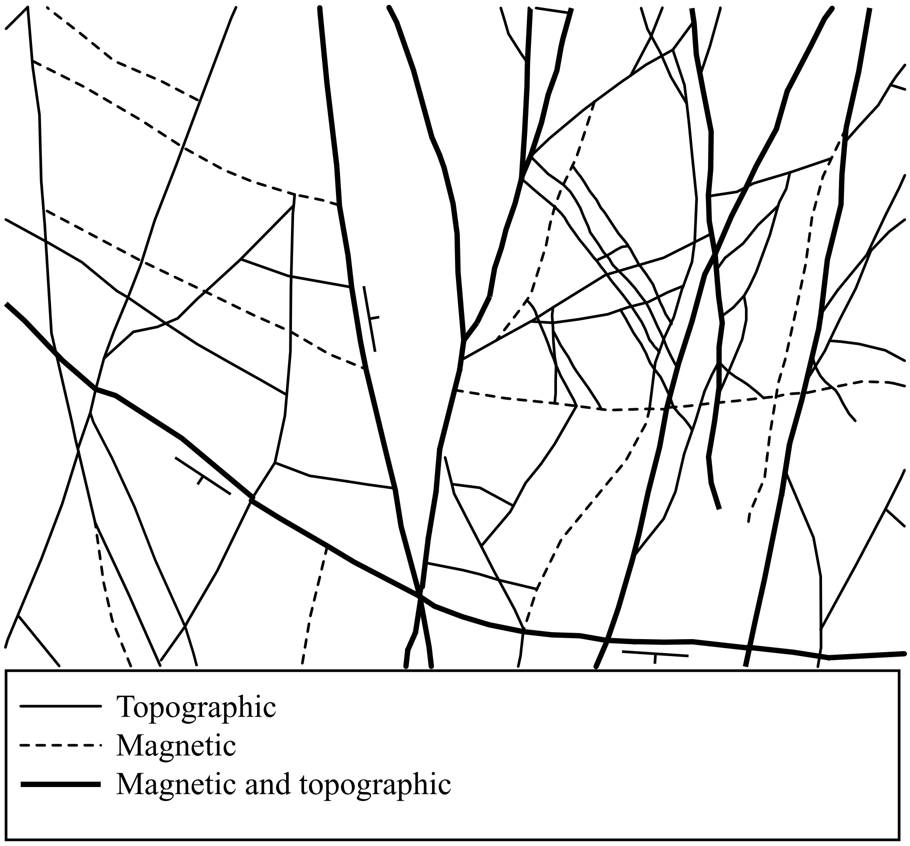

Figure 4-2. Hypothetical example of a lineament map.

4.1.2 Deformation zone maps

At an earlier stage in the detailed investigation of a site, a lineament map of the surroundings of the site exists, with the corresponding descriptive document (Section 4.1.1). Subsequently, the lineaments defined need to be further investigated, in order to determine their dimensions and geological character. This is mainly done by a specific investigation of the lineaments with the help of detailed geological mapping of bedrock outcrops, possible excavation of trenches, drilling of shallow boreholes in the vicinity of the lineament, mapping of Quarternary deposits and surface geophysics. These are aimed specifically at determining the character of the lineaments, and the results consist of preliminary bedrock and soil maps and presentations of geophysical data, using method-specific processing and interpretation, and accompanied by descriptive documents. This new and problem-oriented database must then be integrated with the existing lineament map (itself an integrated product, see Section 4.1.1), a process which is the subject of the present section.

The aim of the integration of the new data with the lineament map is, in the first instance, to classify the lineaments geologically. Since a major focus of SKB's work on site characterisation is to identify deformation zones, this classification is then used to filter out all lineaments which have no significance in this respect, to produce a *deformation zone map*. On this map, all lineaments which have been determined to represent the surface traces of deformation zones are shown as such, and have been classified as confirmed or probable, and if possible, according to the type of deformation (brittle, ductile, or composite). Also, all lineaments whose character could not be determined unambiguously are retained, and designated "possible" deformation zones.

This is in line with international practice in radioactive waste research, where, for reasons of conservativeness, unclassified lineaments are considered to be the traces of deformation zones (zones which are assumed to be hydraulically and rock mechanically important) until proved otherwise.

Process of integration

The process of integration which leads to the production of a deformation zone map is shown schematically in Figure 4-3. The work is carried out by a geologist and a geophysicist in cooperation, whereby both should be familiar with the conditions at the site. Access to modelling tools for the geophysical data must be assured, as well as the competence to use them. Before work commences, all information is processed for use in a GIS environment. The products of the method-specific processing and interpretation of the different investigation methods are prepared, together with the integrated lineament map (Section 4.1.1). In addition, profiles prepared from the surface geophysics data should be available, in preparation for carrying out supplementary modelling.

The earlier integrative interpretation and the new method-specific processing and interpretation can have resulted in the following products:

- The integrated lineament map, with its descriptive document.
- An outcrop map, geological data from the exposed bedrock, and a preliminary bedrock geological map (from geological mapping of outcrops and trenches).
- Data on the soils, and a preliminary soil distribution map (from soil mapping).
- A soil thickness map (from refraction seismic surveys and Ground Penetrating Radar, GPR) and an interpretation of seismic low velocity zones in the soil, if possible with an estimate of velocity variations within the zones (from refraction seismic surveys).
- Delineation of electrical conductors in map view, together with quantitative interpretation of the conductor's dip, conductance and depth below the surface (from VLF and Slingram), or, if the electrical conductor is broad, its width, conductance and depth below the surface (from Slingram).
- Delineation in map view and in profile of low resistive zones and estimates of the variations in electrical resistivity in 3D (from resistivity measurements).
- Delineation in map view of elongate zones in the bedrock with low magnetic susceptibility, and a model of the zones width, dip and depth below the surface (from magnetometry).
- Delineation of dislocations in the aeromagnetic anomaly patterns.

The existing lineament map, together with the results of interpretations from the ground geophysical investigations, outlined above, give a series of different suggestions as to the width and extent of the lineaments. Within each set of lineament boundaries, one can at this stage only give the interpreted physical properties, such as P-wave velocity, magnetic susceptibility and resistivity. In general, the significance of these data for characterising the lineament is unknown. Hence, the process of integration takes place in two steps: first, the creation of a single model for the boundaries of the lineaments, then, the evaluation of the geological significance of the lineament, i.e. classification as confirmed, probable or possible deformation zones, or other features (see below). The classification

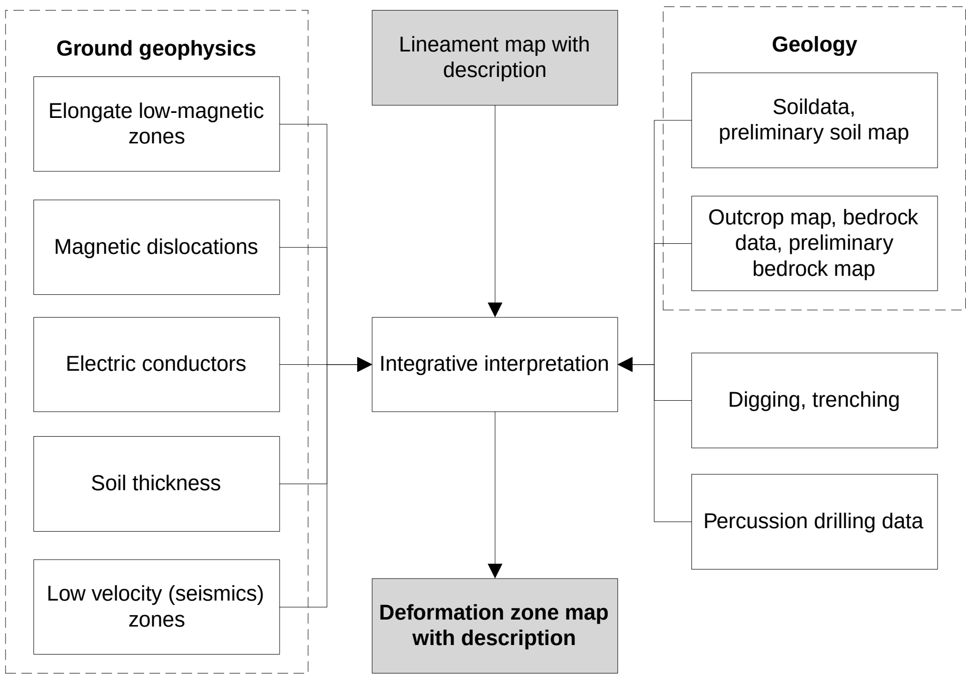

Figure 4-3. *Flow diagram showing the procedure envisaged for the integrative interpretation of the deformation zone map, on the basis of available and/or newly acquired geological information and the results of geophysical ground surveys.*

will be mainly based on observations from the geological mapping, together with data from the trenches and shallow drillholes. Hence, the work process can be summarised as follows:

- compare the alternative boundaries of the lineaments with each other,
- if necessary, model the geophysical data,
- relate the alternative boundaries to the geological information,
- integrate the alternatives to a common model which shows the boundaries of the lineaments,
- classify the lineaments with the help of the geological information,
- describe the integrated map, pointing out the main inconsistencies between the different alternatives and indicating the reasons for the decisions made.

The end result of the process is a *deformation zone map* (Figure 4-4), which is simply an update of the existing lineament map (Figure 4-2), with the lineaments classified according to geological significance. The map contains both lineaments whose character has been determined and lineaments whose character is unknown. The lineaments whose character has been determined included initially both deformation zones and zones which are not associated with deformation in the bedrock, such as those caused by Quaternary depositional processes (e.g. eskers) and those caused by human activities. Of these, only lineaments which proved to be, or are probably, the traces of deformation zones are retained. Some will be *confirmed* (character known on the basis of direct geological evidence), and others will be *probable* (character deduced from indirect geological and/or geophysical evidence). Lineaments whose character is still unknown after this phase of investigation are retained on the deformation zone map as *possible* deformation zones, for reasons of conservativeness.

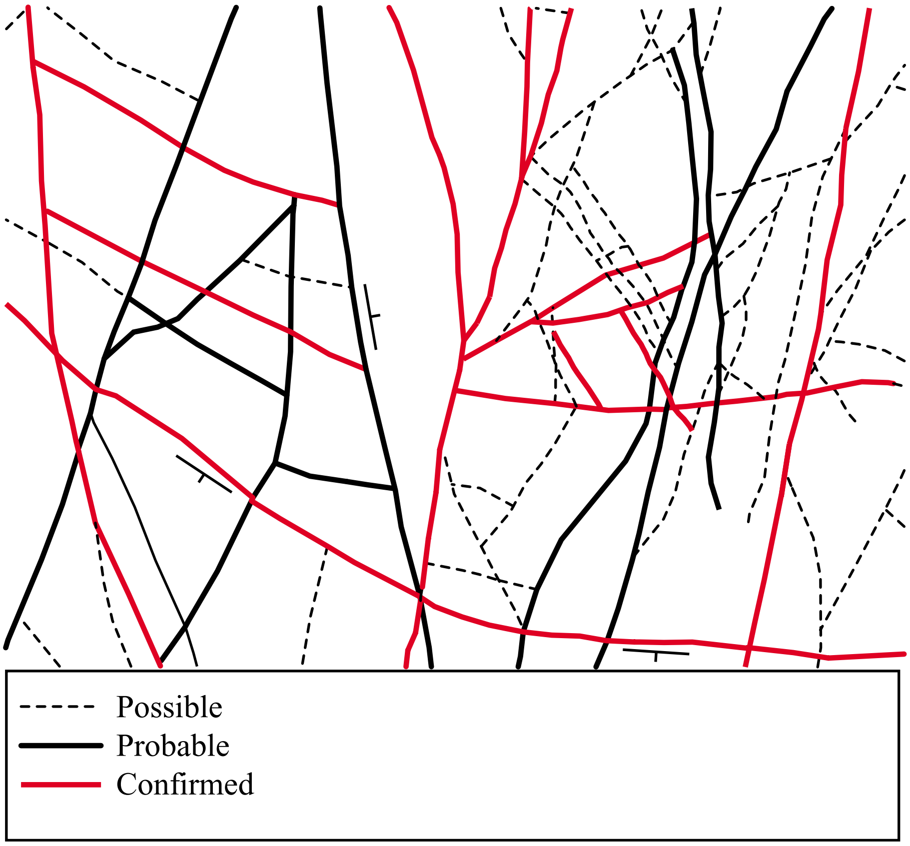

Figure 4-4. *Transformation of the hypothetical lineament map shown in Figure 4-2 into a deformation zone map (for explanation, see text).*

Hence, the end result of the integration process is a map with confirmed and probable deformation zones, and "possible deformation zones", which are simply lineaments for which there is as yet no evidence of their geological significance. The deformation zone map contains the base elements necessary for a 2D structural model of the bedrock surface of the site, with a certain amount of depth information from the upper part of the bedrock. This result is stored in SDE and RVS.

4.1.3 Lithological maps

At an early stage in the site investigations, method-specific processing and interpretation exists for geological data from outcrops, gravimetric data and airborne geophysical data. These form the basis for an integrative interpretation of the surface distribution of rock types at the site and in its surroundings. In areas of very low relief, processing and interpretation of the geological and airborne geophysical data mainly provides a 2D representation of the Earth's surface, whereas gravimetry gives somewhat more information on conditions at depth.

The input data from bedrock mapping consists of direct observations of field relationships, rock analyses and observations under the microscope, which have resulted in an outcrop map with descriptive document. The data from geophysics results mainly in a geometrical subdivision of the area into homogeneous domains/volumes and the petrophysical properties which are measured in outcrops and on samples which represent those domains/volumes. This subdivision reflects the rock distribution in the area but does not allow the different units to be designated according to normal geological reasoning, unless outcrop conditions are sufficient for calibration. For this reason, the subdivision is sometimes called "pseudo-geological". Some parts of the geophysical data base give some geometrical information on the extension of these pseudo-geological units in the third dimension, allowing, for instance, the dip of contacts between units of different properties, or the depth to different units, to be estimated.

The aim of integrative interpretation, in this case, is to couple the information on rock types with results from the outcrop mapping, which is located at discrete points, irregularly distributed throughout the area, to the different geometrical frameworks which have resulted from the geophysical investigations. The integration process essentially yields a description of the rock type distribution in 2D, but data from particularly magnetometry and gravimetry give some 3D information down to a few tens to a few hundreds of metres depth, depending on the objects character, and on its surroundings. This is presented in the form of a *lithological map* (lithological map of the bedrock surface with the soil removed), accompanied by a descriptive document.

Process of integration

The process of integration is illustrated in Figure 4-5. The work is carried out by a geologist and geophysicist in co-operation. Access to modelling tools for the geophysical data must be assured, as well as the competence to use them. Before the work begins, all the information is finalised in a form which can be processed in a GIS environment. The products of the method-specific processing and interpretation, and supporting material from the SKB SDE and SICADA databases, are prepared for use. Supporting material can, for instance, mean general petrophysical data. Furthermore, geophysical data in the form of profiles is accessible, to be able to carry out geophysical modelling, if required.

The products of the method-specific processing and interpretation include the following:

- An outcrop map, showing the position and extent of the main exposures of bedrock, keyed to petrographic descriptions in an accompanying descriptive document, which also includes any other indications of the position of geological boundaries in unexposed areas.
- An overview description of the expected density distribution in 2D and 3D, whereby the different densities can be expected to correspond to different geological units.
- The boundaries in map view of units with different magnetic properties, such that the units can be expected to correspond to different geological units. A certain amount of information on the extent of the units in the third dimension is also obtained.
- The boundaries in map view of units with different radiation spectra, such that the units can be expected to correspond to different geological units.
- The boundaries in map view of units with different electrical conductivity. This generally gives information on structures, but in certain cases also on rock types. The latter applies particularly to occurrences of graphite schist and sulphide-bearing rocks, neither of which are likely to occur within potential sites.

The geophysical techniques give a number of different geometrical frameworks from the method-specific processing and interpretation. Within the unit boundaries, only the interpreted properties can be defined, for instance, the content of K, U and Th, magnetic susceptibility, or density. A high density and a low content of K, U and Th is

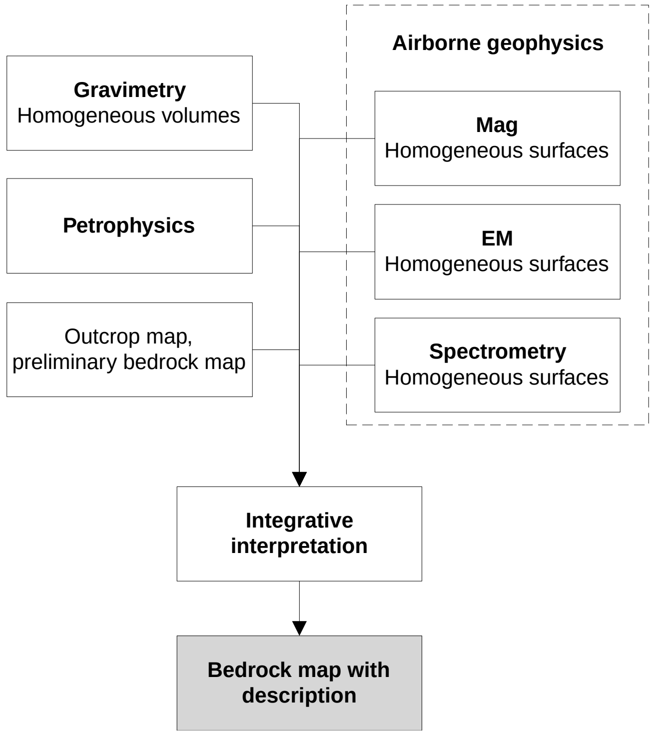

Figure 4-5. *Flow diagram showing the process of integrative interpretation envisaged for the production of a lithology map, using the results of airborne geophysics, gravimetry, petrophysical data, and outcrop mapping*

usually taken to indicate basic rocks, but it is desirable that this indirect indication be complemented by a direct observation of the rock, if possible. Such information can also be obtained from the outcrop map, with descriptive document, and yields a more secure and precise extrapolation.

The process of integration consists of, first, the integration of the different boundaries suggested on the geophysical maps and, then, the classification of the units defined, mainly using the geological information. The work process can be summarised as consisting of:

- classifying the units geologically, mainly based on the results of the outcrop mapping and analysis of rock samples,
- comparing the alternative boundaries on the geophysical maps with each other,
- modelling the geophysical data, if necessary,
- integrating the alternatives to a common map with geophysically characterised units,
- describing the process of integration to produce the final lithology map, discussing the problems encountered and the reasons for the proposed solutions.

The result of the integrative interpretation is a lithological map (an interpreted map of the bedrock surface with the soil removed), with a descriptive document, i.e. mainly a 2D representation, but with a certain amount of depth information (Figure 4-6). This result is stored in the SKB SDE and RVS systems.

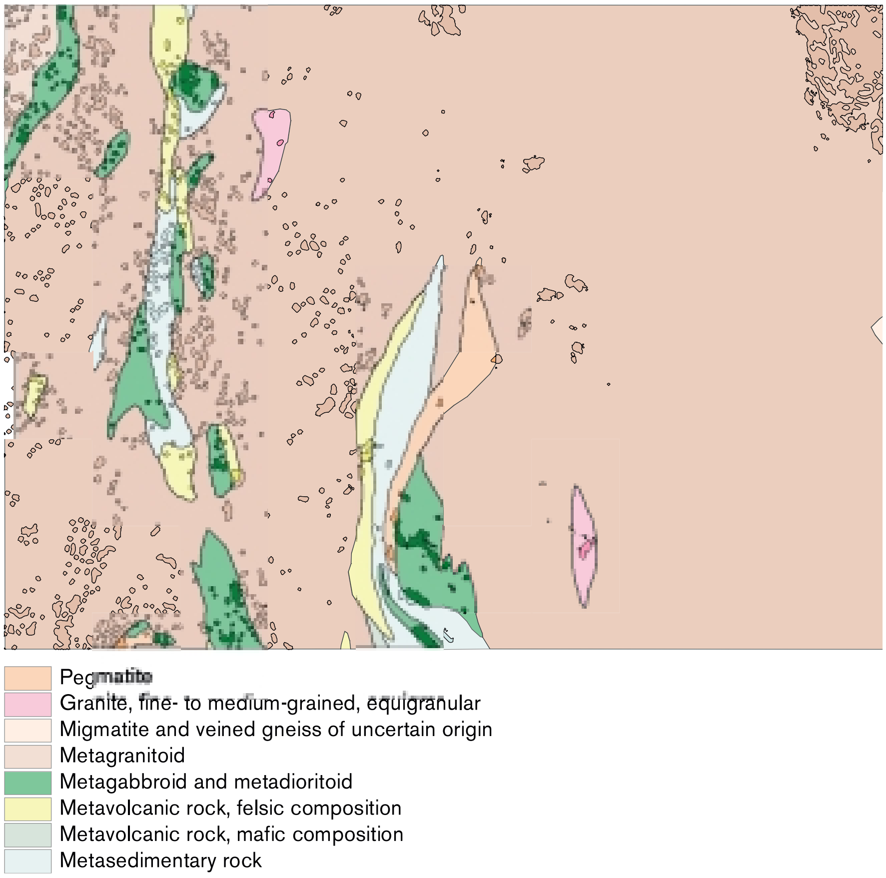

***Figure 4-6.** Hypothetical, lithological map of the area illustrated in Figure 4-2 and Figure 4-4 showing mapped outcrops and interpretation of lithology.*

4.1.4 Bedrock maps

A bedrock map is a geological map of the bedrock surface underneath the soil cover, and shows both deformation zones and rock types. It is essentially a combination in GIS of the deformation zone map and the lithology map, produced according to the procedures outlined above. It is the end product of the process of integrative interpretation which leads to a 2D cartographic model of the geological conditions at the bedrock surface of the site. Figure 4-7 shows the 2D bedrock model of the Forsmark regional model area as it appears in the report describing the site descriptive model version 0.

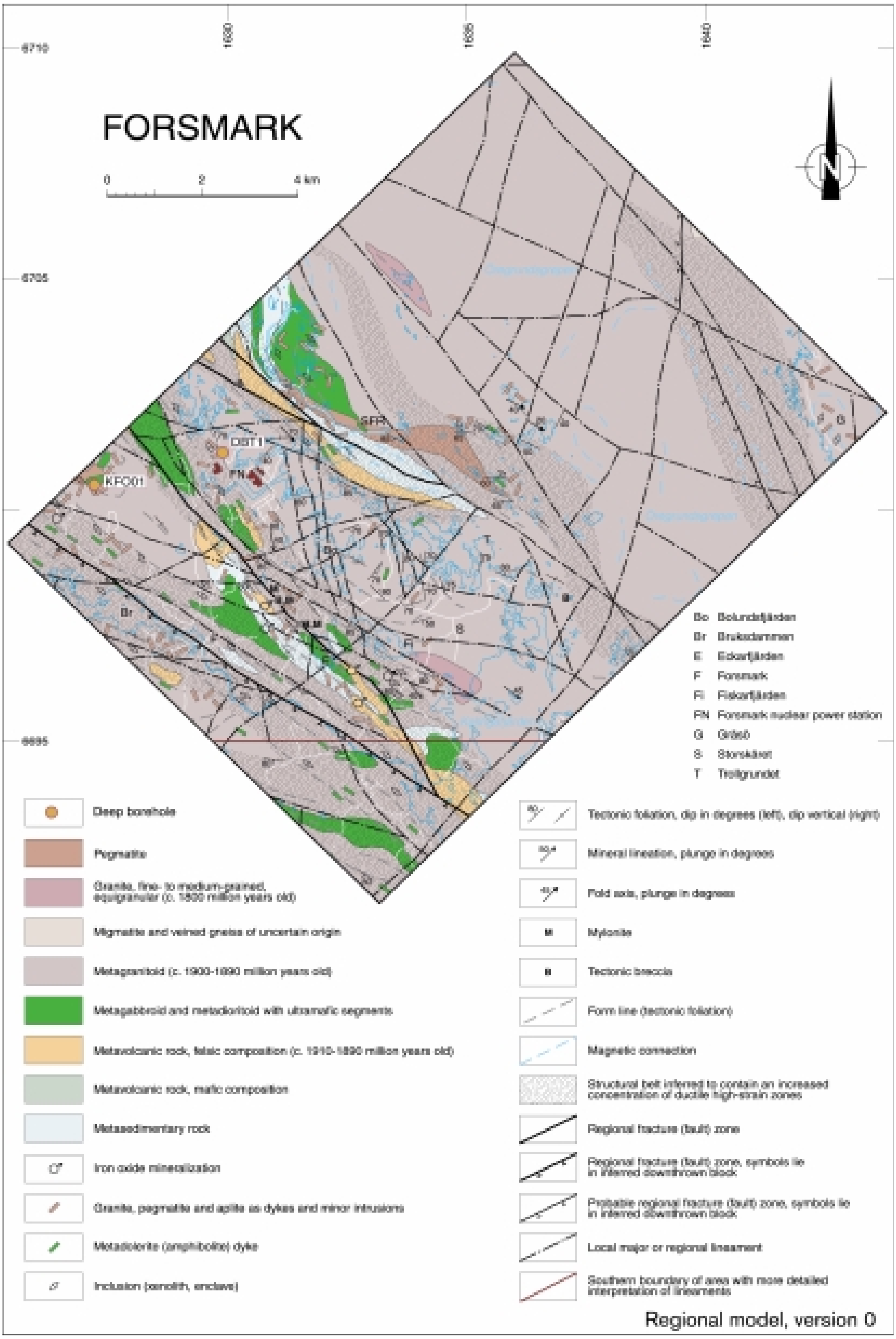

Figure 4-7. *Bedrock map of the Forsmark regional model area /SKB, 2002, Figure 4-4/, i.e. a 2D cartographic model for the bedrock geology of the area, with the soil removed.*

4.2 Preparation of single borehole interpretations

The preparation of geoscientific maps through the integrative interpretation of geological and geophysical data at the Earth's surface leads to a series of 2D models, with their descriptive documents, which provide the input to RVS along the upper surface of the site descriptive model (Section 4.1). To start the process of 3D modelling, a similar procedure with similar aims must be carried out along each individual borehole, as outlined in the present section. The end result of this procedure is a single borehole, or, more briefly, a *single hole interpretation*, which consists of an integrated borehole log or series of logs (equivalent to the maps of the last section) and an accompanying descriptive document. The aim is to establish a system of linear control lines through the model volume, which together with the geoscientific maps provide a stable framework for the subsequent 3D modelling (Chapter 5). However, it should be kept in mind that "stable" in this context is a relative term. Neither the geoscientific maps nor the single hole interpretations are to be regarded as primary data. Both are the result of integrative interpretation, and both are subject to revision in the light of subsequently acquired data (such as the excavation of a trench across a hitherto soil-covered area, or the use of a new borehole logging tool). As such, they are to be regarded to present the current view in the site descriptive modelling process.

With regard to single hole interpretation, a fundamental distinction must be made between cored boreholes and percussion-drilled boreholes. Rock cores, which with present-day techniques can be taken with very little core-handling damage and almost 100% oriented, are the key to dependable single hole interpretation and are therefore indispensable in the early stages of site investigation and site descriptive modelling (Section 4.2.1). Together with borehole-wall TV images, they provide good evidence of bedrock conditions at depth, and the lithological and structural logging of the cores and TV images together, provide a reliable data base. Geophysical borehole data are of secondary importance in this situation, although still providing important supplementary information. On the other hand, single hole interpretation of percussion-drilled holes is heavily dependent on the geological interpretation of the geophysical logs. Hence, percussion drilling has a different role to play, not as a dependable part of the initial modelling framework, but rather as a rapid and cheap method of model testing at a later stage, at a time when sufficient experience from core drilling and core description has been accumulated to be confident that the TV images and geophysics from non-cored holes can be correctly interpreted. With this distinction in mind, we treat single hole interpretation of cored boreholes and percussion drilled boreholes rather differently in the descriptions below.

4.2.1 Cored boreholes

The general process of single hole interpretation of cored boreholes is shown as a flow diagram in Figure 4-8. The sequence synthesis – classification – interpretation shown on Figure 4-8 will be used as a framework for the descriptions below.

Core/BIPS synthesis

The key element in single hole interpretation of cored boreholes is the synthesis of the data obtained from the systematic lithological and structural logging of the cores with those obtained using the BIPS tool, or some other system for optically imaging the borehole walls. For short, we will refer to the result of this process as a *core/BIPS synthesis* (Figure 4-8). This usually takes place off-site, in a specially constructed core laboratory (Figure 4-9), in which the whole core or large sections of core can be

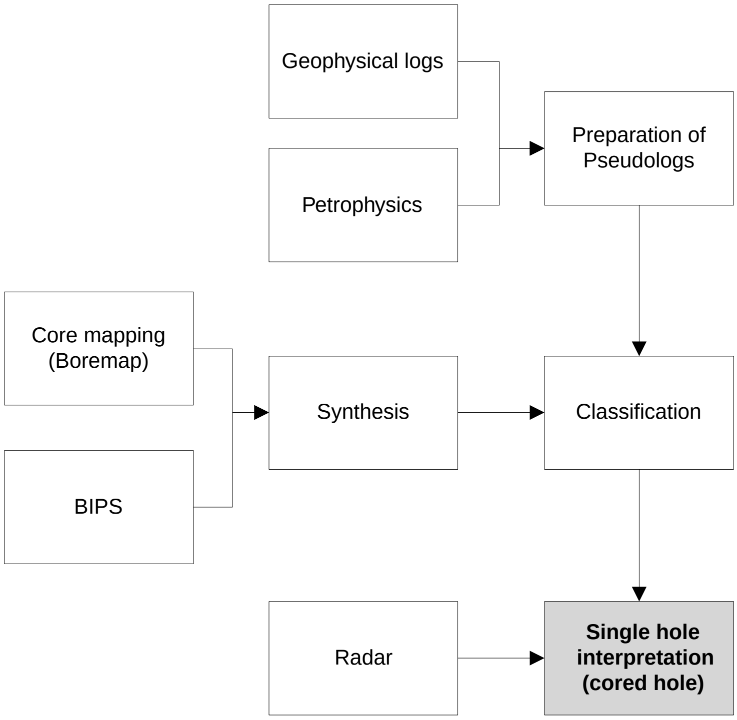

Figure 4-8. *Flow diagram to illustrate the different steps in the process of single hole interpretation of cored boreholes.*

comfortably observed, side-by-side with a display of the BIPS images (Figure 4-10). At SKB, this procedure has been developed under the name of "Boremap" and includes also the simultaneous display of interpretations of the geophysical borehole logs, as the core mapping (lithological and structural logging) proceeds. However, the critical aspect in this first stage of single hole interpretation is to integrate the core and BIPS data to produce a definitive lithological and structural borehole synthesis. This is necessary because neither the cores nor the BIPS, taken alone, give a complete picture of bedrock conditions along the borehole:

- The cores alone suffer from several deficiencies, which only BIPS-type systems can remove. Firstly, sections of core loss are common, even using modern triple-tube core drilling techniques. Such core loss indicates sections of increased fracturing and/or alteration, which are exactly the sections which are of greatest interest in radioactive waste research. Relations in these sections can be reconstructed from the corresponding borehole-wall TV images. Secondly, techniques for geographically orienting the cores in-hole are generally only partially successful and the percentage of successful core orientation is often far below 100%. The foliation and fracture data bases are then inadequate for the statistical analyses necessary for reliable rock mechanical and hydrogeological parameterisation (e.g. DFN analysis, see Appendix A2). Identification of the same structural or lithological feature on the core surface and on the BIPS images (which are fully oriented) provides a method of retrospectively orienting the core in the core laboratory /cf NAGRA, 1997/. Core orientation is important because of the unreliability of the BIPS images under certain conditions (see below). Thirdly, the fracture parameter, "aperture" (e.g. for hydrogeological modelling), can rarely be measured on core material, but is potentially measurable on BIPS images.

- BIPS images alone suffer from several deficiencies, which only careful comparison with the corresponding rock cores can remove. Firstly, digital images will never be able to replace physical objects as a basis for definitive observation. This axiom was already encountered above, in the treatment of lineament maps (only digital imagery) and deformation zone maps (digital imagery subject to ground control). Secondly, and more specifically, experience has shown that BIPS images generally show a fewer number of fractures than natural fractures mapped on the core. There is disagreement about the reason for this, and whether it is systematic and therefore amenable to statistical correction. However, certain conditions clearly lead to some types of fracture being indiscernible in BIPS, in some lithologies (e.g. micaceous and amphibole-bearing rocks) and in certain structural types (e.g. strongly foliated, mylonitic or migmatitic gneisses). Also, important fracture surface features, such as the types of covering minerals, or the presence, orientation and kinematics of slickensides, can rarely be determined. These deficiencies can only be removed with core observation. Thirdly, particularly in the lower parts of deep boreholes, something equivalent to "core loss" often occurs, blurred strips across the images due to the BIPS tool stick-slipping on the borehole walls. Again, these parts are dependent on core observation for completion.

For these reasons, a complete description of bedrock conditions along a cored drillhole requires, first and foremost, a careful synthesis of the lithological and structural core log data, the BIPS data and the interpretations of geophysical logging data in combination, to be fully reliable.

Figure 4-9. *Drillcore laboratory at the Forsmark site*

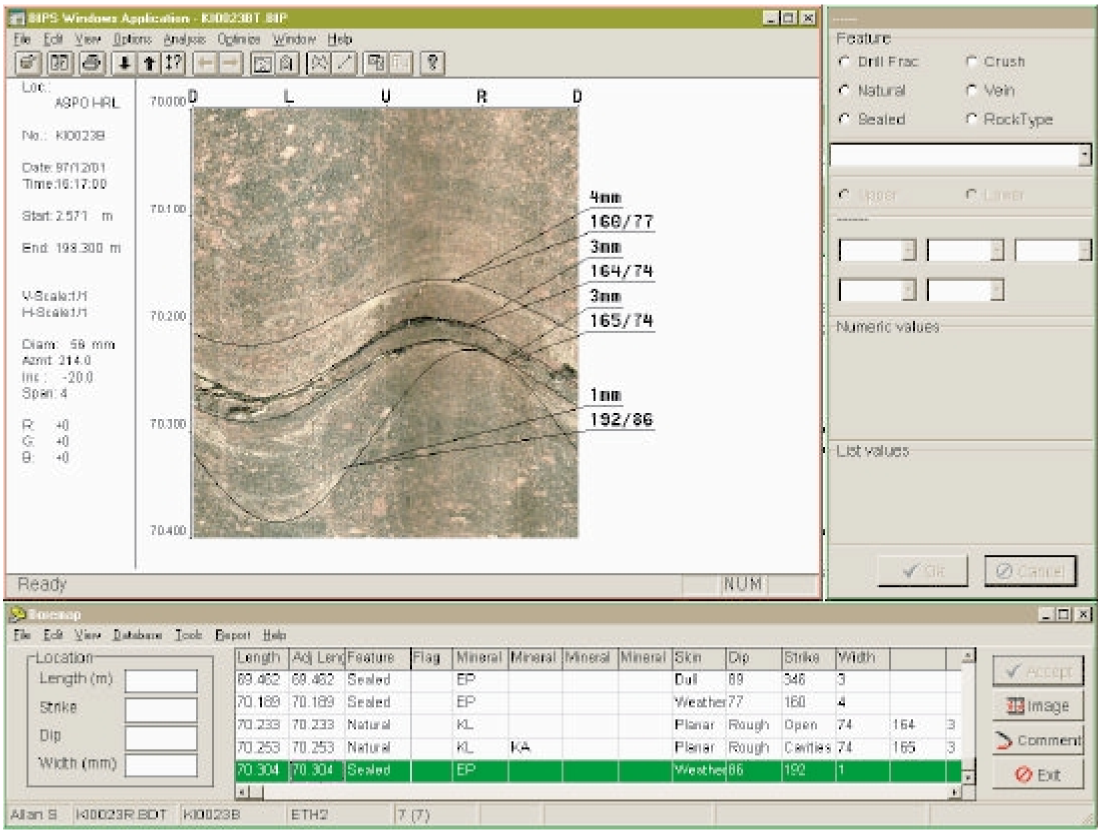

Figure 4-10. *Example of a BIPS image. The picture represents the unfolded drillhole as seen from the inside. Fractures therefore appear as sinusoid curves.*

Apart from the acquisition of reliable and complete borehole characterisation data, core/BIPS synthesis has some specific goals with respect to 3D geological modelling, which only such a synthesis can achieve.

The first goal is to pinpoint and characterise those sections of the borehole which could represent *deformation zones*, for use as fixed control points within the model volume during subsequent 3D modelling. Once a core/BIPS synthesis has been completed and documented, all the necessary data to define deformation zones has been collected, and these data are not themselves likely to be subject to revision. What may be subject to revision is the definition of "deformation zone" (e.g. Figure 2-2), depending on the type of zone, the model scale, and the purpose of the modelling. These definitions are at present under review, but the core/BIPS synthesis will remain as the basis, whatever definitions are chosen.

The second goal is to provide the necessary fracture data for *DFN analysis*. Since DFN analysis must be carried out with statistically sound data sets, every effort must be made to eliminate unsystematic sampling. A core/BIPS synthesis contains the nearest possible approach to a complete fracture data set which is statistically sound, i.e. only containing sampling biases which can be statistically treated (e.g. Terzaghi correction, Appendix A2).

Thirdly, a core/BIPS synthesis aims at encompassing not only quantitative data (such as that required for DFN analysis) but also the qualitative data necessary for improving *process understanding*. A deformation zone is not merely a geometrical element in a model, it is a geological structure in the bedrock, with a particular mode of formation and structural and metamorphic history. Understanding these processes is an important aspect of 3D geological modelling (see Section 4.3).

In the absence of a full core/BIPS synthesis for each cored drillhole, none of these goals can be satisfactorily achieved.

Rock mass classification

The next step in single hole interpretation is *rock mass classification* ("classification" on Figure 4-8), which requires the integrative interpretation of lithological data and structural data from core/BIPS synthesis, with geophysical borehole logging and petrophysical data. This is a two-way process, with the core/BIPS data allowing geological insight into the different geophysical anomalies that the logs display, and the geophysical logs showing continuous along-hole variation patterns in different parameters which are hidden for visual recognition. Integration takes place through the preparation of "pseudo-lithology logs", and/or "pseudo-fracture logs" using petrophysical data (Section 3.2.2), or the semi-automatic combination of the core/BIPS fracture frequency data with different types of geophysical log to produce a "Fracture Zone Index" (see Section 3.2.3) or other rock quality parameters /e.g. Korkealaakso et al, 1994/.

The aim of this step in single hole interpretation is to subdivide the rock mass along the borehole into manageable but meaningful classes. It is not possible to detail here how the rock mass classification should be carried out. Rather, local conditions will steer the basis of the classification scheme. A classification scheme that takes into account various degrees of fracturing, alteration and lithological homogeneity has been implemented in the methodology test at Laxemar /Andersson et al, 2002a/ and was demonstrably of great assistance in the 3D modelling of geological domains. The classification scheme consisted of eight classes that reflect the state of fracturing and alteration in the rock, as well as the lithological homogeneity, as shown in Table 4-1. The classification can be made less subjective by the use of quantitative qualifiers. For instance, a high degree of fracturing could correspond to rocks with fracture frequency exceeding 10 fractures/meter, and the degree of alteration could be coupled to the system recommended by the International Society of Rock Mechanics /ISRM, 1981/. Fracture frequencies are preferentially determined using moving averages with varying window sizes as demonstrated in the methodology test /Andersson et al, 2002a/.

Table 4-1. Classification of rock based on lithology, alteration and fracturing. "Single" and "mixed" refer to whether the rock in the class is dominated by a single rocktype or better classified as mixed lithology.

Homogeneity	Alteration	Fracturing	Class
Single	Low	Low	R1
Mixed	Low	Low	R2
Single	High	Low	R3
Single	Low	High	R4
Mixed	High	Low	R5
Mixed	Low	High	R6
Single	High	High	R7
Mixed	High	High	R8

Lithological homogeneity, or heterogeneity, is a practical concept in situations where many different rock types are intermingled. For instance, the dominant rock type at Äspö is a granite (Smålandsgranit) with mafic xenoliths and sheets or lenses of fine grained granite. The latter have been shown to have great hydrogeological importance. Deterministic modelling of these relatively small, but numerous, rock volumes is impractical. It is therefore desirable to be able to separate domains where the dominating granite is intermingled with xenolith and sheets of fine grained granite from domains where these are scarce or absent. In terms of communication, it has been shown practical to use the term lithological homogeneity in this respect. Though not intended for quantitative estimation of the homogeneity, Figure 4-11 illustrates schematically the concept as it would have been applied to Äspö.

Another aspect of importance for rock mass classification is lithological isotropy, or anisotropy, i.e. the degree to which the rock has been foliated and/or lineated during ductile deformation. This aspect was not considered at Laxemar (Figure 4-12), since all rocks were isotropic, but in other situations it can be important feature, particularly for the definition of ductile deformation zones. Rock anisotropy also has significant rock mechanical implications.

The purpose of rock mass classification is to facilitate the modelling of a site in 3D, in a way which is meaningful for the aims of the modelling (basic site geometry, rock mechanics, hydrogeology, etc). The choice of proper qualifiers for classification must be reflected in the local geological conditions at the site and the type of data available at the time of modelling. Subjectivity in classification is, therefore, not only a necessity but also desirable. This is because it allows the use of different classification systems within the same site, reflecting the different needs of the recipient or user of the model, i.e. whether it is intended for repository design or safety analysis, or for any of the numerous groups using the geometrical framework of the geological 3D model as input to their modelling efforts (e.g. hydrogeological models, rock mechanical models, transport models, etc).

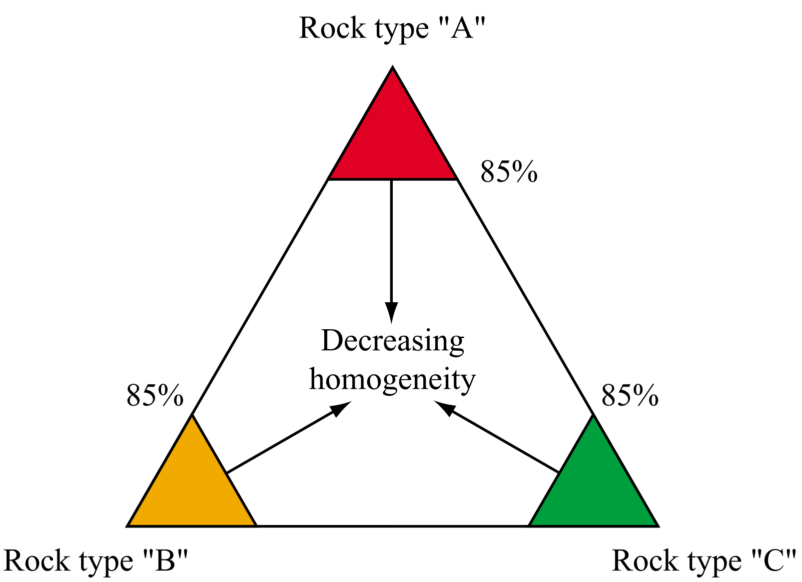

Figure 4-11. *Schematic illustration of the concept of "lithological homogeneity".*

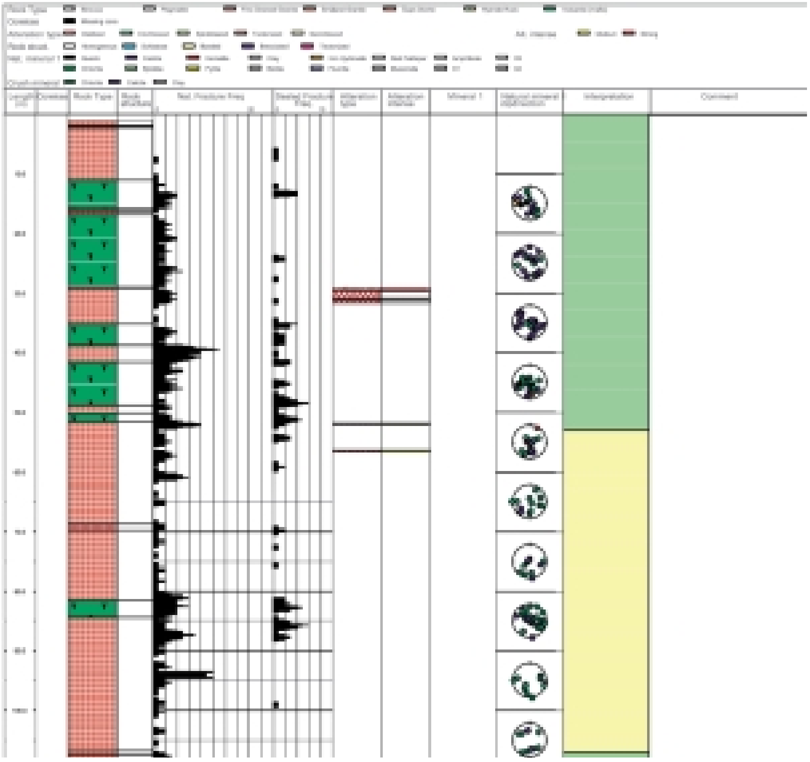

Figure 4-12. *WellCad log of KLX01 showing lithology, fracturing and alteration along the borehole used in the Laxemar methodology test /Figure 3-8 in Andersson et al, 2002a/. The classified rock segments are shown as coloured boxes in the interpretation column.*

Single hole interpretation document

The end-product of single hole interpretation of cored boreholes is a document containing the results of the core/BIPS synthesis and the rock mass classification steps, with the arguments behind the definitions and subdivisions used, and with a discussion of any further interpretative possibilities. One method, borehole radar, which is commonly included in this further interpretation, is shown on Figure 4-8, and a common aim of further interpretation is to extrapolate features observed in 1D along the core, such as deformation zones, into the rock volume immediately surrounding the core, thus contributing to the 3D reconstruction. Here, there are few general guidelines, and the problem of extrapolation will be taken up again in Section 4.3.

4.2.2 Percussion-drilled boreholes

As noted above, percussion-drilled boreholes do not yield the same reliability of basic lithological and structural data, because of the almost complete absence of the rock cores representing concretely the bedrock to be described. For this reason, this type of drilling is not usually used for basic site characterisation purposes, but reserved for special tasks which lay more weight on rapid and cheap operation. Typical tasks in this category are, for instance, shallow drilling through the soil cover to check or complete the bedrock map of the site, or, in advanced stages of site descriptive modelling, directed drilling to test hypotheses concerning the location of postulated lithological boundaries or deformation zones within the site model volume. Nevertheless, the geological interpretation of BIPS, geophysical logs, drilling data, cuttings, etc, in combination has reached a high degree of sophistication, especially when the same techniques have been "calibrated" during core drilling at earlier stages in the site investigations. The general process of single hole interpretation of percussion-drilled boreholes is shown as a flow diagram in Figure 4-13.

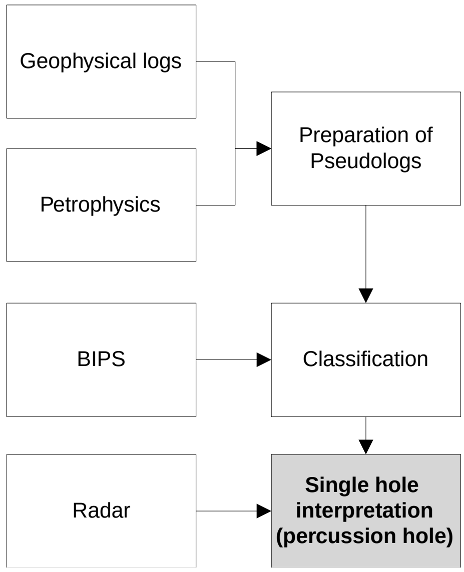

Figure 4-13. *Flow diagram to illustrate the different steps in the process of single hole interpretation of percussion-drilled boreholes. Note that some geological data is obtained from analysis of the drill cuttings (rock chips brought up by the drilling fluids), the colour and consistence of drill flushing water, and the drill sinking speed measurements, not mentioned in this diagram.*

The general procedure of data acquisition and processing, through the preparation of "pseudo-logs" (Section 3.2.2), to a rock mass classification system, and, finally, together with other geophysical data (e.g. borehole radar), to a single hole interpretation, is the same as for cored boreholes, and will not be repeated here (see Section 4.2.1).

4.3 Crosshole geophysics

As the number of boreholes, and hence the number of single hole interpretations, increase, a further activity becomes increasingly important, the correlation of deformation zones, lithologies and rock mass classes between neighbouring boreholes and eventually throughout the model volume. For short, we will refer to this process as *cross-hole interpretation* (Figure 4-14). This is an activity which one might think was best done with the help of RVS (Chapter 5), since the approximate alignment of fixpoints with similar characteristics in several different boreholes in definite planes can easily be investigated with the RVS 3D viewing capabilities. However, by cross-hole interpretation we mean the accumulation and compilation of evidence on, for instance, the orientation and extent of deformation zones, which is based on intrinsic data rather than geometrical coincidence.

Without going into details, the kind of activities and data which under different circumstances may be important, particularly for distinguishing between the probability of correctness of different geometrical alternatives, can be summarised as follows:

- standardisation of definitions and descriptive templates according to site conditions and modelling aims, so that similar features can be recognised in the different single hole interpretations, and single hole interpretation documents converge towards a common terminology and process understanding (mode of formation of rocks and structures),

- continued use of in-hole, cross-hole and hole-to/from-surface geophysical techniques, from relatively simple methods, such as borehole radar (for extrapolating, for instance, deformation zones into the rock volume immediately surrounding the borehole) to sophisticated seismics,
- continued development cross-hole and multi-hole hydrogeological testing techniques,
- use of any available modelling analogues for methodology testing, particularly the development and testing of correlation methodologies combining geological and geophysical techniques in available underground excavations (SFR, Äspö),
- development of process understanding on the scale of the site and its surroundings (geological history, tectonic setting, see Table 5-3), which could involve further, goal-oriented geological investigations in off-site areas (e.g. similar but better exposed areas in the wider surroundings of the site).

In carrying out multi-hole interpretation, the site geologist and site geophysicist should be present during at least some of the work, amongst other things to be able to elucidate the diagnostic level of the investigation methods used, but also to be able to contribute with their detailed knowledge of the site. For example, it is important that discussions of alternative interpretations of tomographic results are based on knowledge of the cross-hole methods and of the geological conditions at the site. In addition to results from geological and geophysical methods, data from other subject areas, such as hydrogeology, should be included in multi-hole interpretation. This can often reduce the ambiguities which arise in the course of interpretation with an inadequate data base. Hence, representatives of those subject areas which are being used in the interpretation should be present when appropriate.

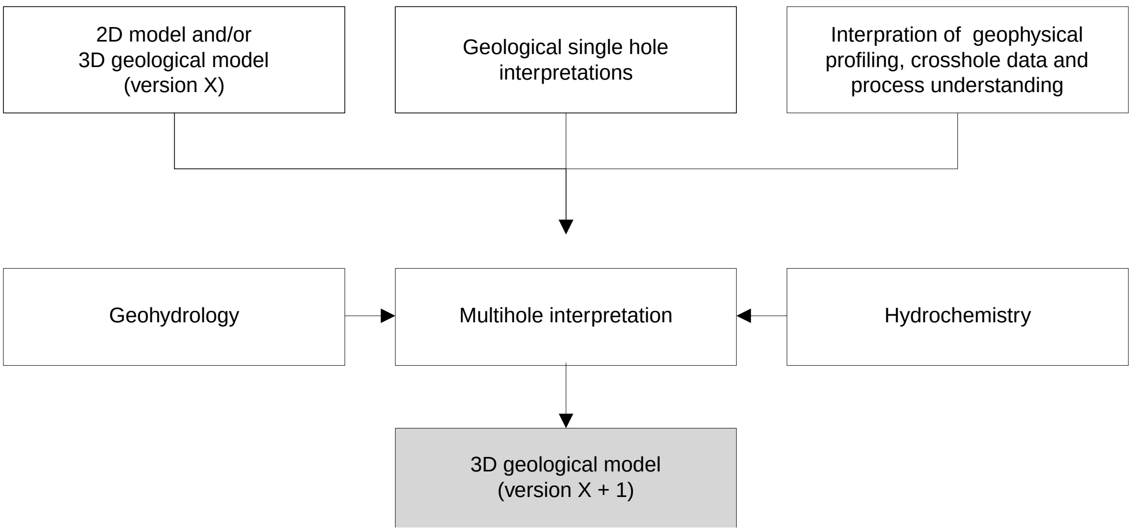

Figure 4-14. *Flow diagram to illustrate the process of multi-hole interpretation, i.e. integrative interpretation of geological single hole interpretation, geophysical in-hole and cross-hole measurements, and process (and site) understanding.*

However, a key element in multi-hole interpretation is *process understanding*. Without a conceptual model of the way in which the features formed, correlation and predictive modelling becomes impossible, because arguments to distinguish between different geometrical possibilities cannot be formulated. Process understanding not only covers the overall genesis, but particularly, in the case of site characterisation and single hole interpretation, the relationships between core-scale and site-scale features which the process has produced. This can be illustrated with reference to deformation zones.
It is an easy matter to build a conceptual model of a site-scale ductile deformation zone and all the related core-scale structures, because such structures are known from the scientific literature to follow kinematic rules which result in typical structural relations (e.g. Figure 4-4). This means that a single cored drillhole through a ductile deformation zone can result, through analysis of the structural relationships observed in the core, in a conceptual model which can be used directly to extrapolate outwards into the surrounding rock volume. From the conceptual model one obtains directly a predictive capacity.

The situation is quite different in the case of brittle deformation zones, since fracturing is a much more unpredictable process at a core-scale, and there is a much weaker scientific basis for telling how brittle deformation at site scale (e.g. the scale of a regional or major local fracture zone) leads to a particular constellation of core-scale features. It is difficult to construct a convincing conceptual model for a brittle deformation zone, and hence extrapolation outwards from a fractured zone in a borehole is extremely speculative. Without process understanding and a corresponding conceptual model, the predictive capacity is low. Hence, for brittle deformation zones (which are those of greatest interest for rock engineering and hydrogeology), every attempt needs to be made to improve process understanding, in the context of multi-hole interpretation.

5 Process of 3D modelling

In practice, the interpretation of geological information forms the basis for the establishment of a geometrical framework which will subsequently mature to be manifested in a geological model. This will be modified and altered in the processes of iterative and integrative interpretations and eventually form one part of the site descriptive model.

In this chapter we describe how the primary data from site investigations (Chapter 3) and the results of integrative interpretation of cartographic and borehole data (Chapter 4) are used to construct 3D geological models.

In Section 5.1 below, we outline the main principles of modelling and introduce the reader to notions specific to 3D modelling. Section 5.3 describes the modelling of a deformation zone by detailing the coupling to primary data (Section 5.3.1) and using illustrative examples aimed to express the process of actually building the model in 3D (Section 5.3.2). Section 5.3.3 explains how properties of the model components are handled whereas the process of building domains, based on these properties, is described in Section 5.3.5. Modelling of uncertainties requires special attention and the modelling process is, for clarity, separately described in Chapter 6. Other aspects of the modelling regard implementation of routines for technical auditing, quality assurance, etc. Though not strictly essential for the process of 3D modelling, we nevertheless include a discussion of the matter and describe its implementation in RVS in Appendix A3.

5.1 Modelling principles

During site investigations, data from the site are accumulated in SKB's databases (SICADA and SDE), which constitute the main sources of primary data and cover all scientific disciplines. The data in SICADA are georeferenced, i.e. are coupled to observation points on the surface, in a borehole or along a tunnel. SICADA stores both primary data and data derived from method-specific interpretation, such as routinely calculated hydraulic conductivities.

The methodology for constructing geological models proceeds such that primary data (see Chapter 3), and the results of integrative interpretation (geoscientific maps, single hole interpretations, see Chapter 4) are retrieved from SICADA/SDE and visualised using an appropriate tool, such as RVS (Figure 5-1). The visualisation of the primary data and interpreted products is achieved by a direct coupling between RVS and selected parts of SICADA. Based on the visualisation of primary surface and underground data, possible correlations and structures are identified and later interpreted with regard to position and extent. RVS is used to visualise measured point values in boreholes and on the ground surface or along planes representing geophysical, geological, chemical, rock mechanical or thermal point measurements on reflectors, profiles or maps. Using these data as a starting point, alternative interpretations can be tested in an iterative process which leads to the geometrical elements of the site being created in RVS.

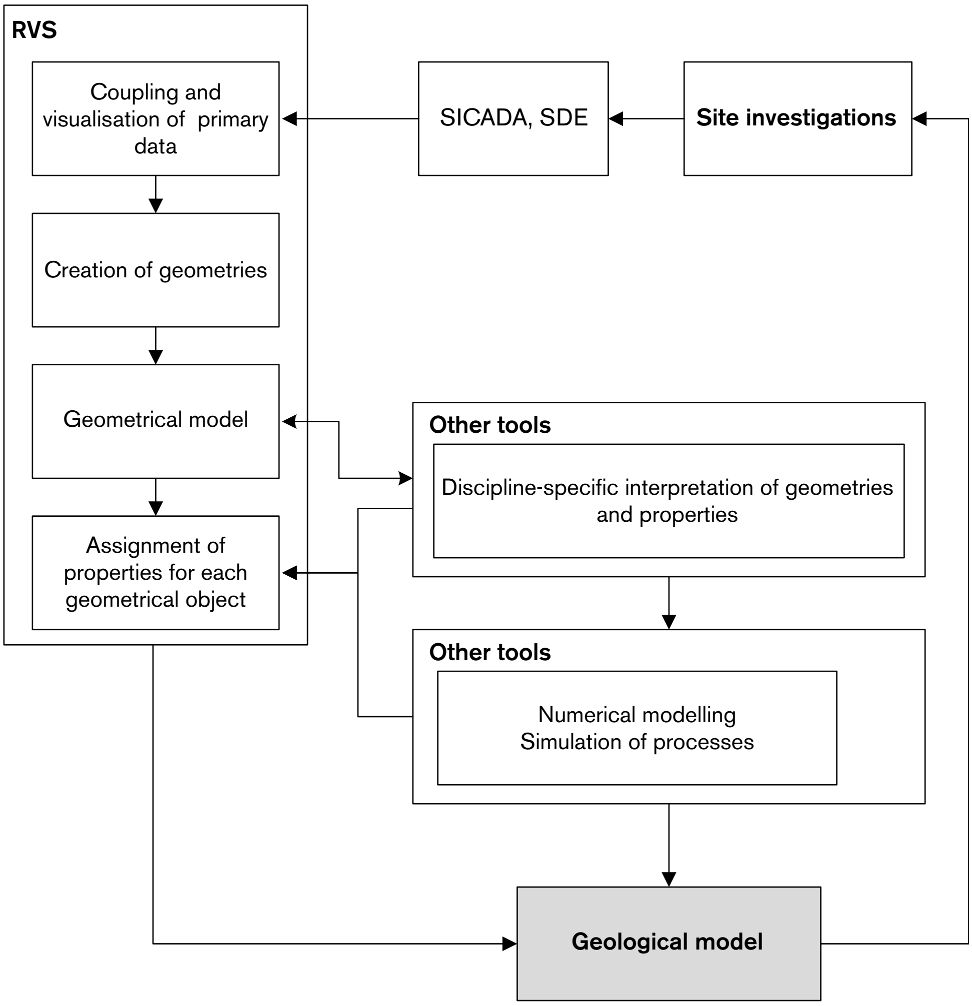

Figure 5-1. *Schematic flow diagram for the process of constructing a geological model, using geometric reconstruction in RVS and interpretation/analysis in an iterative process, based on information from the databases.*

The methodology of establishing a geometrical model of the site is systematically iterative, but at the same time flexible, so that aspects of the model can be modified according to the needs of any user. In order to guarantee a correct version management (see Appendix A3), as well as the compatibility and logics of the model construction, it is necessary to strictly follow the following principles:

- Models at different scales within the same investigation area should lie in the same coordinate system. This means that models at different scales can exist together in a so-called "nestled system".
- The geometrical model needs to be described at all points, that is, so-called "space filling". This means that the model is filled by geometrical objects in such a way that no part remains undescribed.
- It must be possible to alter the extent and form of every single object whenever necessary during the modelling process. It must also be possible to remove objects, but all operations must be traceable.
- The primary data and the origin of the interpretation of each object need to be traceable directly from the model.

- User rights determine what possibilities exist for modifying object types.
- It must be possible to export the geometrical model to other types of modelling tools. To achieve the highest possible compatibility, surfaces are therefore represented as polygons (triangulated surfaces).

A systematic building up of the geometrical model guarantees traceability backwards in time and provides possibilities for comparisons between, e.g. different model alternatives. Models grade successively from being strictly geometrical to becoming more geoscientific by the definition of the types of objects and the assignment of interpreted geoscientific characteristics. The following stepwise and iterative modelling methodology is suggested for the building of geometrical models at different scales:

1. The model volume is defined.
2. Relevant primary data from SICADA, which have been quality controlled, are visualised.
3. Relevant 2D models in SDE are visualised.
4. Correlations and structures are identified, whereby different interpretation alternatives are tested in an iterative process.
5. The structures which have been thus identified are interpreted geometrically using RVS, which was specially developed for this task.
6. Object types are defined for the interpreted geometries (see Section 5.2, for definition). In this context, information which has not been stored in SICADA, for instance technical reports, must also be considered.
7. Characteristics are assigned to the interpreted geometries (see Section 5.3.3).

5.2 Model components

A geometrical model contains the geometries of deformation zones, rock units and larger fractures (deterministic elements). Depending on modelling scale, the model may also contain geometries for the bedrock surface, soil, water and air. In addition, the model may contain boreholes, shafts and tunnels which, together with the geology, can be used, for example, for borehole planning, for the technical design of underground excavations or as a basis for subsequent modelling.

The geometrical elements in the geometrical model do not contain any information, except for the coordinates, until they have been assigned to an *object type*. Object types can be thought of as a group of geoscientific parameters which together describe the geological character of the element, for example, a geological structure. Without assignment to an object type, it is impossible to know what a particular geometrical object represents. Apart from defining what a given object represents, the object type also provides a coupling to the geoscientific properties of the object.

A geometrical model can contain all the classes of object which are encompassed by classical (Euclidean) geometry, namely points (dimension D = 0), curves (D = 1), surfaces (D = 2) and volumes (D = 3).

For example, in order to define a fracture zone, the first step is to create a surface (2D) or a volume (3D) derived by analysing the available primary data. The object is then given the object type designation "deformation zone" and receives a link to a data sheet listing the properties relevant for the description of deformation zones, such as strike, dip, RMR (Rock Mass Rating), number of fracture sets, permeability, etc. If the object represents a dyke, for instance, then the appropriate object type is "rock unit", which means that characteristics relevant to describing the rock type, such as grain size, degree of foliation, porosity, etc, are linked to the object via a corresponding data sheet.

Hence, the principles for linking geometrical objects to a suitable set of parameters (characteristics, properties) can be formulated as follows:

- Every object must be assigned to a particular object type. The object type tells 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 which are regarded representative for the whole volume of the modelled object. If this is not possible, the object must be subdivided into smaller units. Properties can be either single values or a statistical distribution valid for the whole volume of the object.
- The type of object and its properties must be capable of being changed and updated at any time during the modelling work. However, the right of a particular user to modify the object type is controlled by a previously established rights protocol. Normally, these rights are linked to a specific subject area (see Appendix A3).

Table 5-1 shows the different classes of geometry and the object types which are available for each class. The following paragraphs discuss some of the details, with reference to this table. Curves and surfaces are modelled as made up of linear and planar segments.

Lineaments of different types are the most commonly occurring 1D object types and are represented by curves in the model. Lineaments will be collected together as a separate 2D cartographic model, which will be used as a background model, or template, for the 3D models.

Boreholes can be represented as lines or curves, based on coordinates, preferably through visualisation of data from SICADA and single hole interpretations.

2D surfaces are used to completely or partly subdivide the model. Such surfaces can comprise the boundaries between different domains, or single structures, such as deformation zones, dykes or rock contacts. However, deformation zones of significant size are usually assigned a thickness in the model and hence they are preferably modelled as volumes.

2D surfaces can also be derived from GIS or can be created directly in RVS. However, such surfaces will most probably only serve as intermediate steps in the modelling process, for instance, when rock and soil maps are to be imported from GIS for modelling 3D objects. Nevertheless, 2D objects will play an important role, since it will be through them that traceability to the original interpretations can be established. As with lineaments, it will be necessary to create special 2D models, which will then be used as background for the 3D models.

Table 5-1. Table showing the relation between different geometrical classes and the different object types which can be assigned. The present general types in the table are used in order to give the modeller some flexibility as the methodology is developing. Work is at present under way to set up detailed parameter lists for the different object types.

Geometry	Type	Remarks
Point	Point	Points are usually visualised directly from SICADA.
Curve	Lineament	Lineaments are usually imported from GIS.
	Planned boreholes	
	General curves	
Surface	Ground surface	Topography can also include drainage system and seafloor topography.
	Bedrock surface	
	Deformation zone	Local minor fracture zones and single large fractures can be represented by surfaces, rather than volumes (see below).
	Boundary between rock units	Separating two or several rock units.
	Boundary between soil units	Separating two or several soil units.
	General surface	
Volume	Deformation zone	Regional, local major and certain local minor zones are modelled as volumes.
	Rock units	
	Soil units	
	Water units	Lake, sea.
	Tunnel	
	Shaft	
	General volume	

Rock units are used to designate parts of a rock block within which a particular property (parameter) is thought to be constant or to be representational by a statistical distribution. In a first step, the block is subdivided on the basis of rock type, using the 2D geological model from GIS as template. As the amount of information increases, other subdivisions will become possible, according to other properties, such as degree of fracturing or rock quality, in which case these will be defined as domains (see Chapter 0).

Tunnels, shafts and boreholes are those object types which may be included as man-made constructions in the model.

An object can only be described as one object type, i.e. can only be interpreted as belonging to one particular category. Hence, each volume can only be described by a given number of parameters. This apparently very restrictive principle, however, gives rise to significant advantages in terms of the management of the object-related data and the quality assurance of properties which are associated with that object. For instance, for a diabase dyke which is strongly fractured, it could seem appropriate to be able to designate the object as belonging to both the "rock unit" and "deformation zone" object types. However, many of the parameters which belong to the object type "rock unit" are represented, albeit in another form, in the object type "deformation zone", for example, the parameter "rock type". A strongly fractured diabase dyke can thus be assigned to the object type "deformation zone", with its specific fracture parameters, with the parameter "rock type" being specified as "diabase". The search tools in RVS are planned so that the user is given the possibility of visualising different aspects of the object. The modeller will be able to choose either to view the object as a, for example, deformation zone, or as a dyke consisting of a certain type of rock, or as both, depending on the search criteria used.

Another situation which can arise is that a deformation zone intersects two (or several) different rock types. The object will be assigned to the object type "deformation zone" in the model, and then there will be two possibilities in subsequent modelling. The zone can be modelled either as a single object, in which case the dominant rock type is specified, or as several objects with object type "deformation zone" but different sets of parameters for "rock types". Of these possibilities, the second is preferred. This certainly increases the number of objects, and hence the complexity of the model, but, with the help of the grouping function in RVS, based on the search criteria, the user can still visualise the deformation zone as a single object. In the following section we will apply the principles outlined above to hypothetical but representative examples.

5.3 Modelling sequence

In this section we describe, using worked examples, the modelling process by showing how a geological structure is built up using a compound of primary- and semi-interpreted data.

Deformation zones outline the rock blocks of interest for layout of deposition tunnels. In addition, being essentially 2-dimensional in geometry, deformation zones are fairly simple to model. Hence, geologists have traditionally initiated their modelling efforts by defining the deformation zones. The remainder of the model volume represent the host rock which can be further subdivided by modelling rock- or domain boundaries (see Section 5.3.5) using the same or similar techniques.

The following modelling sequence is commonly applied:

1. visualisation of primary data,
2. creation of structural surfaces honouring observation points and/or previously established models,
3. applying truncation and intersections of structures if appropriate,
4. assigning characteristic widths to the modelled structures using the structural surfaces as templates,
5. assigning representative properties to the modelled structures,
6. assigning representative properties to the remaining volumes.

Explicit modelling of geometric uncertainties can be done within the sequence outline above but, as argued for earlier, such uncertainties require special consideration and we regard it practical to detach such uncertainty modelling into a separate modelling process. The models can always be merged at a later stage if considered appropriate.

Geological features are commonly modelled in the following sequence:

1. Topography (including lake and sea floor).
2. Deformation zones.
3. Rock boundaries.
4. Domains.

Local conditions might, however, alter this sequence. For instance, it might sometimes be more appropriate to model domain boundaries before deformation zones. Furthermore, it might be advantageous not to model the topography at all in regional models, especially in areas of low relief, since topographies are complex geometrical objects and might have an adverse effect on computing performance.

The topography and rock surface together yield a volume that can be further subdivided into soil units or domains. We do, however, not for the moment anticipate any need for explicitly modelling soils in the 3D geological model. Considering that soils constitute a very thin layer on top of the modelled rock, and for all practical reasons therefore can be regarded as mainly 2-dimensional, we here argue that soils should preferentially be handled in GIS. Nevertheless, soils might be sufficiently dominant in high resolution, small scale models that explicit 3D modelling gives added value. Since the technique of creating soil units is identical to rock units, we leave the creation of soil units unattended in the examples below.

5.3.1 Primary data visualisation

The first step in 3D modelling is to visualise primary data. The main sources of primary data needed for 3D modelling are the geological 2D model, i.e. the geological map, and borehole data. Though such data are often amalgamated, it is practical for 3D modelling purposes to detach relevant parts of the information and treat each part separately. In this section we use, for demonstrative purposes, a simplistic set of hypothetical data.

Topography

Digital terrain models (DTM) provides data for creating the topography and the upper boundary of the rock volumes to be modelled. It is practical to initiate 3D modelling by defining all boundaries, including the topography. 3D modelling of the topography is a fairly straightforward process. From a digital terrain model, e.g. Figure 5-2, elevation data is imported to RVS from either SICADA or SDE as coordinate triplets. The creation of a topographic surface is handled by built-in routines in RVS.

Topographic surfaces are, however, not always suitable in 3D modelling because such wealth of coordinates can hamper computing performance considerably. The inclusion of topography in a 3D model must be balanced with the gain of having it included. Generally, topography is not judged necessary in regional 3D models whereas topography is essential in higher resolution models that will include soils.

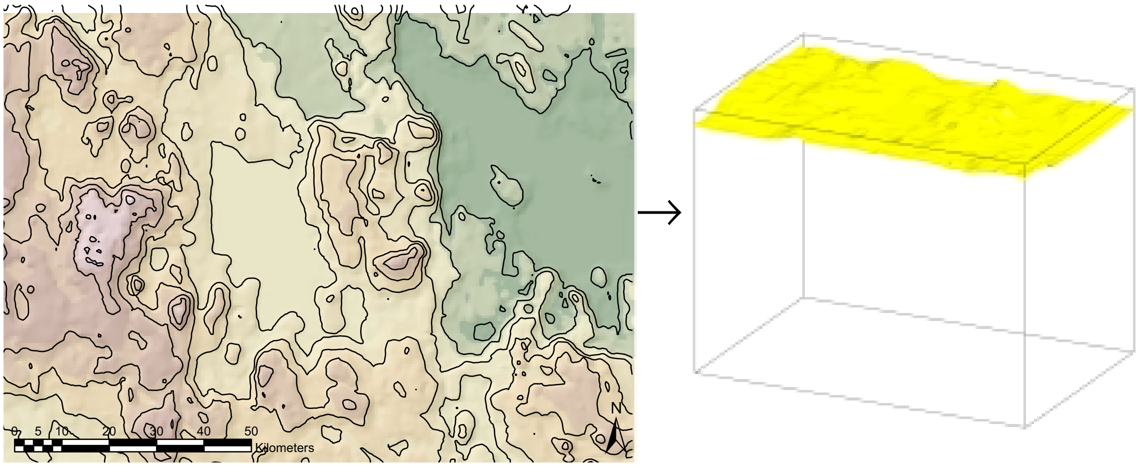

__Figure 5-2.__ A tentative digital terrain model (DTM) is used as input for the creation of the topography in 3D models.

Geological map

Geological maps (e.g. Figure 5-3) can be considered as 2D models. However, this is not entirely correct. In fact, the geological map usually provides the modeller a substantial amount of 3D information. For instance, fabrics, rock boundaries and deformation zones are usually presented with symbols indicating both their local strikes and dips; the shape of lineaments, in relation to the topography, indicate roughly the direction of dip, etc.

This information, based on outcrop mapping and geophysics, will, paired with conceptual knowledge and local expertise, provide sufficient 3D information that a rough 3D model can be constructed.

The main task for the modeller, in this step, consists of breaking down the amalgamated information into manageable pieces, and to filter out the unnecessary information. It is also common, but not mandatory, to outline domains in this step.

Using the map on Figure 5-3a as example, it would be practical to create a domain for the area in the SW that is dominated by dykes of pegmatite, rather than to model each dyke explicitly in 3D. In addition to boundaries and lineaments that are given by the geological map, the 3D modeller therefore has to create a boundary for the domain (Figure 5-3b). The basis for subdivision into domains is discussed further in Section 5.3.5.

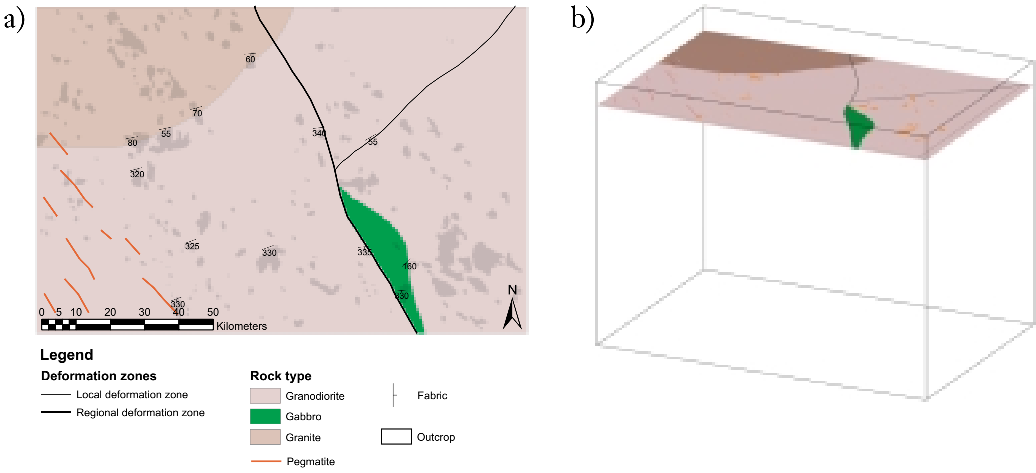

Figure 5-3. *Deformation zones and rock boundaries from the geological map (2D geological model) are used as templates for the construction of surfaces and, later, volumes in 3D models.*

Borehole data

Borehole data are stored in the database SICADA. For each borehole there is a wealth of information that can be displayed for the modeller. The amount of information available is, however, generally too vast to be handled simultaneously. It is therefore practical to summarise some of the information into new entities and use those entities instead. For instance, it is more practical to calculate and display fracture frequency (Figure 5-4a) than to display all mapped fractures and base the 3D modelling on that information. In fact, the process of single hole interpretation (Section 4.2) is aimed to simplify the complex data by combining fracture frequency with lithology (Figure 5-4b) and other parameters into borehole sections considered internally homogeneous (Figure 5-5). Single hole interpretation can therefore be regarded as the 1-dimensional equivalent to domains (see Section 5.3.5). It is therefore natural to initiate borehole visualisation, and in fact 3D modelling, by displaying single hole interpretations if such are available. Additional information is displayed (i.e. incorporated into the model) when necessary.

Certainly, the modeller cannot rely entirely on single hole interpretations. Valuable information such as the local strike and dip of a deformation zone can only be obtained by other means, for instance reflection seismics, borehole radar (Figure 5-5b), BIPS or from the (oriented) core mapping.

a) b)

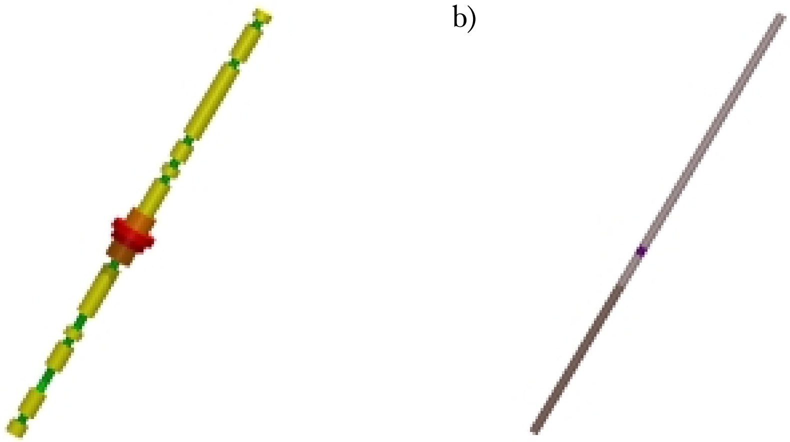

Figure 5-4. Borehole data visualisation. a) Fracture frequency. b) Lithology.

a) b)

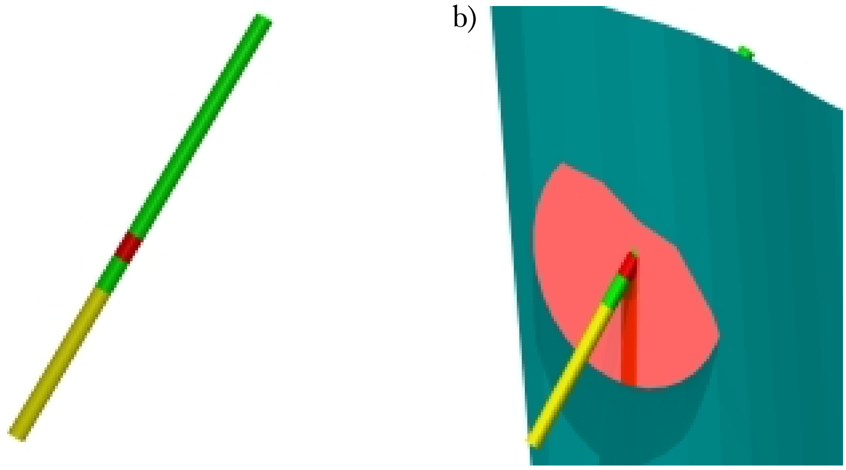

Figure 5-5. *Borehole data visualisation. a) Single hole interpretation. The borehole is subdivided into a few internally homogeneous sections, to ease 3D modelling. b) Borehole radar reflectors can be used to fine-tune the local orientation of, e.g. deformation zone.*

5.3.2 3D interpretations

In this section, we demonstrate how 1D and 2D objects from boreholes and the geological map are tied together to form 3D objects. We assume here that the existence of a structure is confirmed by some method and that it is present on the geological map. There are, basically, only four different situations that are likely to occur:

1. There is no information whatsoever on the dip of the structure. In this case, our recommendation is to not model the structure at all in 3D, but to keep the curve in the model for future use as new information becomes available.

2. The structure can be categorised by circumferential information as being either “steep”, “moderately dipping” or “gently dipping”. In this case we recommend modelling the structure with dips of 90°, 45° and 0° respectively. The uncertainty (Chapter 6) will initially be large but presumably decrease to acceptable levels as new information, mainly drillings, become available.

3. There is only information on the dip of the structure in the form of outcrop observations, geophysical measurement, etc. In this case, the modeller is recommended to use a representative dip and give reference to the source in the model description.
4. The structure is intersected by a borehole. The structure is modelled such that it honours the observation point in the borehole.

Basically, the procedure proceeds as follows:

1. A curve from the geological map, e.g. rock boundary, lineaments, etc, is broken down into streams of coordinates.
2. Boreholes considered likely to intersect the structure are visualised.
3. An appropriate location along the borehole is located and added as a coordinate.
4. A triangulated surface is constructed using these coordinates.
5. The surface is offset parallel to its normal to reflect the thickness of the structure (only applicable to deformation zones, dykes and other sub-planar elements).
6. Terminations against other structures is applied if appropriate.
7. Volumes are constructed using these surfaces as boundaries.

Modelled structural surface

The "*modelled structural surface*" is the surface that is created using coordinates from the geological map, specific points on boreholes and geophysics (e.g. seismics). 3D modelling starts by the creation of modelled structural surfaces which have the following properties:

- Zero thickness.
- Honour observation points.
- Linearly extrapolated between observation points.
- Can either be extended to the model boundary, to another structure (truncation) or terminate blindly.

Using the geological map in Figure 5-3 as example, we extracted the lineaments and created a modelled structural surface representing the regional deformation zone (Figure 5-6a). A representative dip of the zone was obtained by averaging the outcrop observations displayed on the map. Similarly, the local deformation zone was modelled (Figure 5-6b). The geological map shows that the local deformation zone terminates against the regional zone.

The modelled structural surface of the regional zone is adjusted by honouring observations in two drillholes (Figure 5-7). In this example, we have chosen to use the fracture frequency as the basis for locating the zone.

a) b)

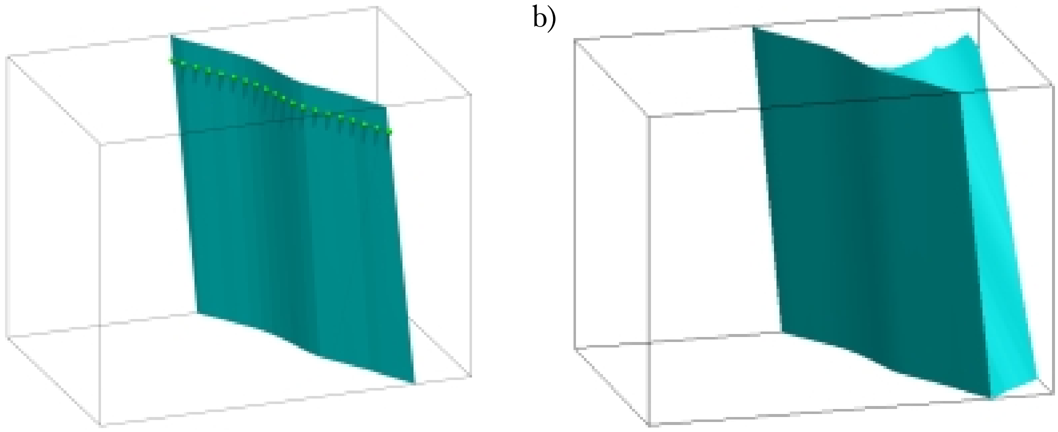

__Figure 5-6.__ a) Modelling a structural surface by using coordinates from lineaments and outcrop observations. b) The termination of the local zone against the regional zone, as seen on Figure 5-3 is implemented in 3D.

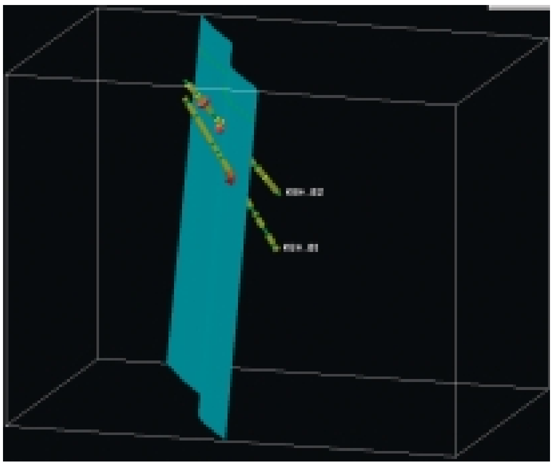

__Figure 5-7.__ Fracture frequency is here used to adjust the dip of the modelled feature.

Modelled structural volume

The thickness of a geological structure, e.g. a deformation zone, is rarely, if ever, constant along the structure and intercepts through the structure will often yield quite different values of thickness. Moreover, the implication of the term "thickness" can differ between various geoscientific disciplines. For instance, rock engineers would typically focus on the fractured part of a deformation zone whereas hydrogeologists would perhaps also take into consideration the porosity in the immediate host rock. As a consequence thereof, single hole interpretations of thickness can be based on quite complex reasoning and are always more or less subjective (see Figure 5-8, for a schematic illustration). It follows, therefore, that estimates of the "average" or "representative" thickness of a modelled structure will often be quite uncertain. Since the scarceness of intercepts rarely justifies strict statistical treatment, the modelling team will unfortunately be forced to base the estimate of representative thickness almost solely on generic knowledge, though backed up by a few borehole observations. We propose that this notion of thickness in the model is given parametrically, as a constant, a distribution or a range, with proper arguments in the model description.

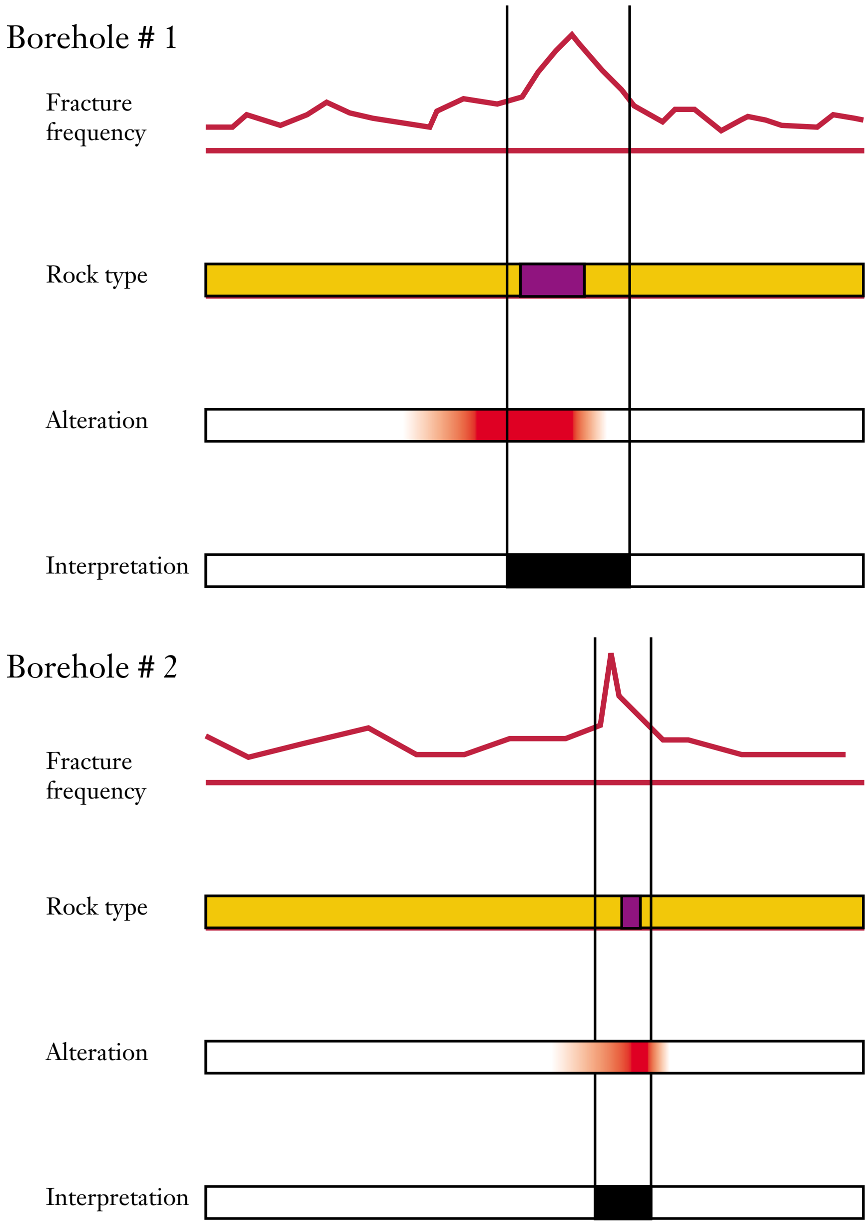

Figure 5-8. *The problem of assigning a representative thickness is illustrated in this schematic cartoon of two tentative single hole interpretations of a deformation zone thickness.*

When modelling the zone as a volume, a so called *modelled structural volume* (Figure 5-9b), the expected thickness, i.e. mean of the distribution or range described above, is used by applying parallel displacements of the modelled structural surface (Figure 5-9a) corresponding to one half of the mean, normal to the best fit surface on either side. In practice, this constitutes no particular complexity since RVS performs this operation automatically.

The choice of using a mean thickness (calculated *or* estimated), a maximum thickness, or any other measure may vary within the same model. Local conditions, available data and the nature of the structure will steer which of the measures is most appropriate. It is therefore of outmost importance that the basis for creating a modelled structural volume is clearly stated in the model description.

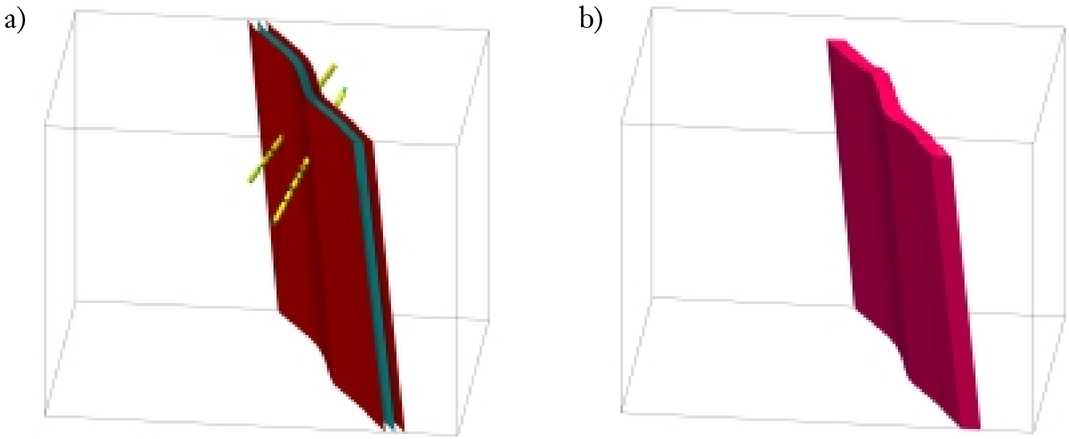

Figure 5-9. *Two aspects of a modelled deformation zone; a) the modelled structural surface (blue) and its normal offsets (red), b) the modelled thickness.*

Modelling rock boundaries

Modelling rock boundaries is similar to modelling deformation zones. The creation of the modelled structural surface is initiated by visualising appropriate information, e.g. the rock contact derived from the geological map and the lithology displayed along the borehole (Figure 5-10). Once defined, the modelled structural surface is combined with other boundaries to outline a rock volume Figure 5-11.

There is of course a practical limit for how small objects it is worthwhile to model explicitly. For instance, a xenolith-bearing granitoid may be modelled as a single object and its xenoliths described stochastically. But if the xenoliths are large, their location is well known and the model has a high resolution perhaps explicit modelling is doable. On the other hand, if the difference in properties between the xenoliths and its host rock is of minor or no importance for e.g. safety assessment, then explicit modelling might not be necessary. With other words, the modeller must balance the detailing of the model with its aim.

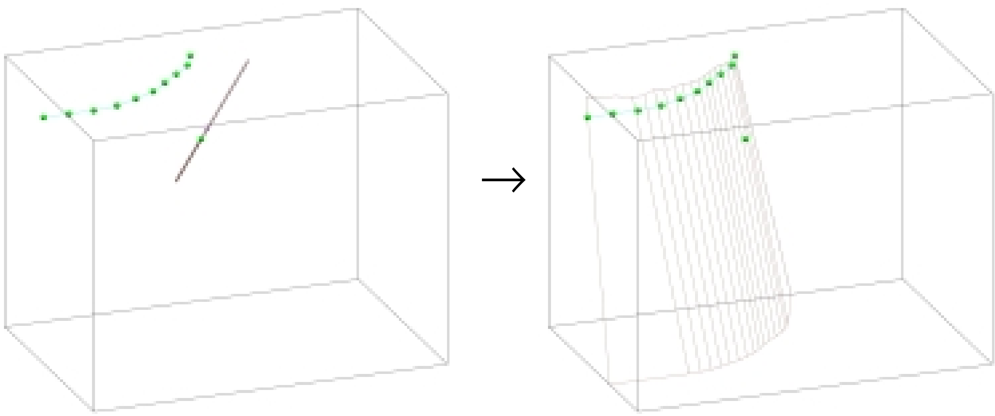

Figure 5-10. *Modelling a rock boundary. a) Coordinates are extracted from the rock contact derived from the geological map. The rock contact is located in the borehole (b) and a modelled structural surface is created using the thus defined coordinates and a representative dip using dip information from the geological map.*

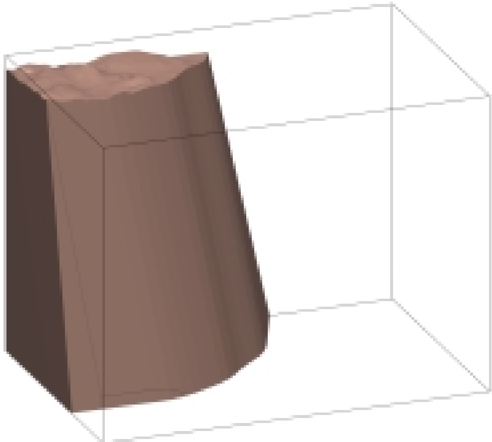

Figure 5-11. *A rock volume can be created once the modelled structural surface has been defined, using, in this case, the model boundaries as additional information.*

In fact, this reasoning is related to the notion of domains (see Section 5.3.5 for a more elaborate discussion). Using the geological map in Figure 5-3 as example, the swarm of pegmatite dykes could be modelled explicitly. This would add a dozen of 3D object to the model. We would prefer, in this hypothetical case, to describe these dykes stochastically. Since the dykes are not bound to any particular rock type, but seem to crosscut both the granite and the granodiorite, we cannot use pre-existing rock boundaries. The modeller therefore has to define a new boundary, i.e. add an interpretation, for the domain dominated by theses dykes. Naturally, this process must be detailed in the model description.

The process of creating a domain in 3D is, however, identical to rock boundaries and will therefore not be repeated here. We do, however, illustrate the end product in Figure 5-12 for completeness.

The procedures outlined above is repeated for each geological feature to be modelled until the desired model is completed. The order in which objects are modelled have no importance on the end result. In Figure 5-13 we show for completeness the remaining features of the 3D model of the map displayed in Figure 5-3.

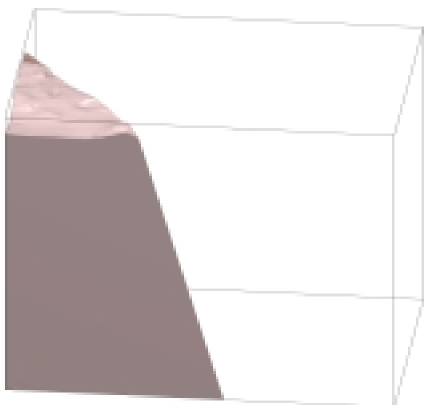

Figure 5-12. *The presence of a swarm of pegmatite dykes (Figure 5-3) forms the basis for this domain.*

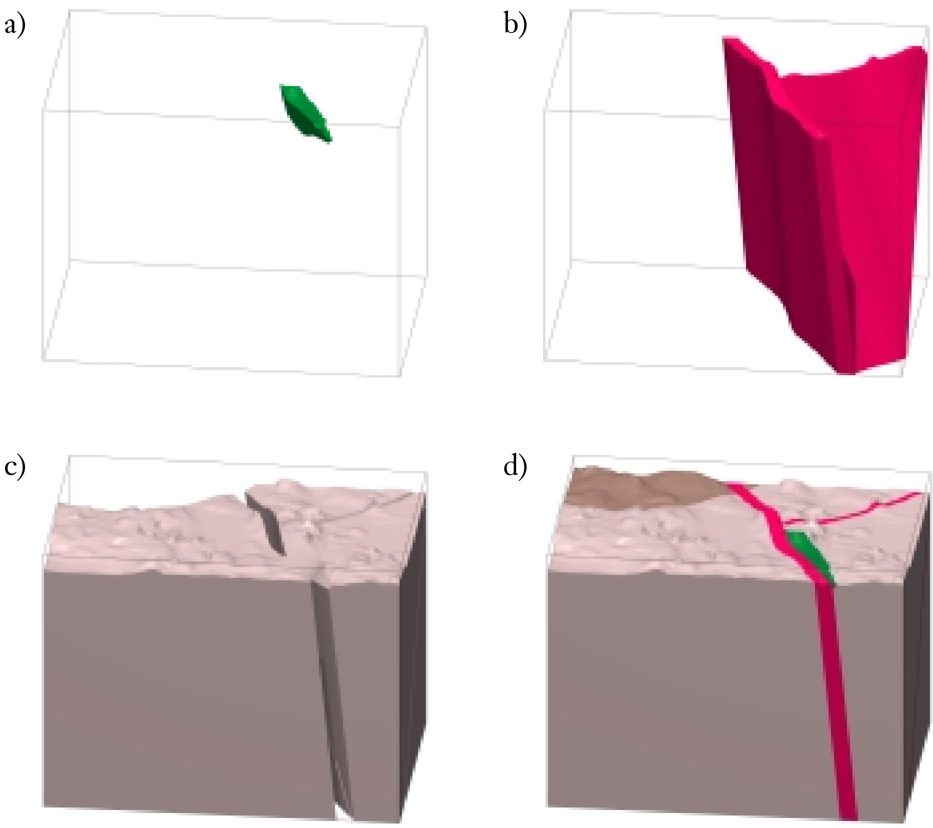

Figure 5-13. Components of the 3D model used as example. a) A body of gabbro, bounded on one side by a deformation zone b) Two deformation zones, one terminates against the other. c) The remaining rock, granodiorite. d) The complete 3D version of the map in Figure 5-3.

5.3.3 Properties of the model components

In contrast to the primary data from SICADA, all parameters that reside in a geological model represent interpretations which are stored together with the geometrical objects in the model. The interpretation of the properties of different objects can be based on data from SICADA, but may also be derived from other sources, such as a published report. The difference can be exemplified with reference to the handling of fracture data. If a fracture zone is intersected by a number of boreholes, the fracture frequency along each borehole can be determined from the structural core logs which are stored in SICADA. From the fracture frequency data, the width of the fracture zone can be *interpreted*. Presumably, the interpreted width will be different in the different boreholes. In the geometrical model, therefore, every fracture zone is assigned a representative width, which may be given as a constant or as a distribution. This information is normally also is linked to the width of the *modelled structural surface*. Hence, it is only interpretations of the primary data which represent the parameter "width" belonging to the object type "deformation zone".

The object type determines with which parameters a given object can be described, although parameters which describe general properties may appear in various object types. The relation between model, object, object type and parameter is shown schematically in Figure 5-14.

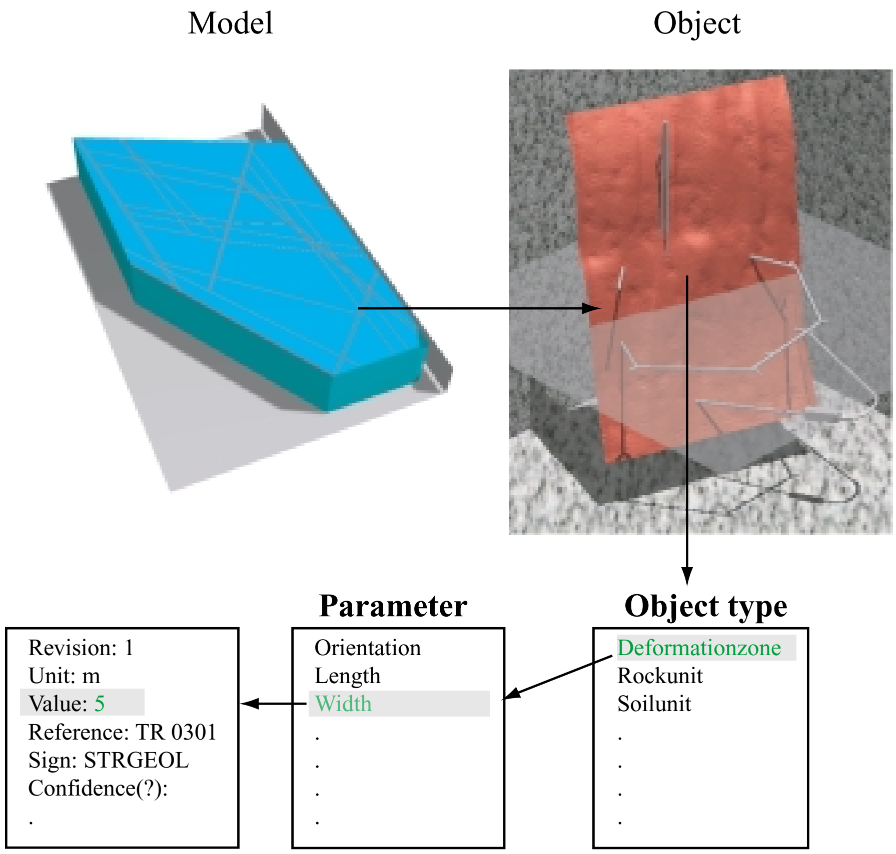

Figure 5-14. *Schematic illustration of the relation between model, object, object type and parameter for each geometrical object.*

5.3.4 Properties to be determined

The assignment of properties, represented by different parameters, is to be done for every type of object in a model progressively, as data from the investigations (interpretation) become available. Properties (parameters) which should be determined during site investigations are given and motivated in /Andersson et al, 1996, 1998/. The sequence and detailing in which parameters will be gathered and how will, however, be defined in activity plans governed by local conditions at the site.

A few properties can be directly assigned to objects in the model by using data gathered in site investigations, for instance rock type. However, a great challenge in geological modelling is to, from a few sparse observations and integrative interpretation, extrapolate sparse data to larger volumes. Some properties can be readily extrapolated by generic knowledge of the geological formation for instance the orientation of the foliation in a deformation zone. Many properties must be subject of special modelling efforts before assignment to object in the model is possible, for instance the stress tensor.

In Table 5-2, we list the properties (parameters) encompassed by the methodology for 3D geological modelling. Remaining parameters /e.g. Andersson et al, 1998/ will either be detailed in the model description or in other methodology reports.

Table 5-2. Properties (parameters) encompassed by the methodology for geological modelling using RVS.

Parameter	Remark
Rock properties	
Rocktype	Represents the *dominant* rock type
Grainsize	Very fine grained, Fine grained, Medium grained, Coarse grained
Structure	Schistose, Banded, Gneissose
Fabric:Type	Foliation, Lineation
Fabric:Orientation	All orientations are given as vectors (trend and plunge), i.e. planes are defined by the orientations of their poles. Orientations can be defined as constants or distributions. For the case of the latter, the type of distribution (usually *Fisher* or *Bingham*) and the measure of spread (usually Kappa, κ) around the mean vector must be defined.
Porosity	All numeric properties can be given as a constant, a range (min-max) or any of the following distributions (including their moments): Normal Lognormal Powerlaw Exponential Though the amount of available distributions is limited to these four, any distribution can be added if necessary
Succeptibility	Numeric
Density	Numeric
Gamma	Numeric
Alteration	Fresh (I), Slightly weathered (II), Moderately weathered (III), Highly weathered (IV), Completely weathered (V), Residual soil (VI)
Fold axial plane	Pole to fold axial plane
Fold axis	Fold axis
Mineral composition	Most common minerals in decreasing order of appearance
Fracture properties (all defined fracture sets can have different properties)	
Intensity	Numeric: Given as intensity measure P32 (m^2/m^3)
Clustering	Spatial correlation of fractures. One of the following models: Nearest neighbour, Baecher, Levy-Lee, War zone, Poisson, Fractal POCS, Fractal Box, Geostatistical (Gaussian)
Size	Equivalent radii
Width	Numeric
Filling	Dominant mineral
Surface roughness: A	Stepped, Undulating, Planar
Surface roughness: B	Rough, Smooth, Slickensided
Weathering	Fresh, Slightly weathered, Moderately weathered, Strongly weathered, Very strongly weathered
Aspect ratio	If fracture shapes are defined as ellipses, the aspect ratio of the axes can be defined
Number of sides	If fracture shapes are defined as polygones, the number of sides can be defined
Direction of elongation	If fracture shapes are defined as ellipses, the orientation of the longest axis can be defined
Fracture termination	
Fracture set orientation	

Parameter	Remark
Deformation zones	Deformation zones can be defined with the same set of properties as the surrounding rock (see above). In addition, the following properties are unique to deformation zones.
Orientation	
Slipvector	Orientation and slip length, if applicable
Length	Applies to the surface trace length of the modelled zone, if applicable
Thickness	
Geometric uncertainty	

5.3.5 Creation and handling of domains

The use of domains (see Chapter 0 for definition) can greatly aid in understanding the geology of the site, by introducing appropriate simplifications, and considerably facilitate 3D modelling. Rock volumes whose properties in one discipline area are regarded as similar can be grouped together for modelling purposes in that area, thus decreasing the amount of objects to be manually handled in the model. Parameters can be assigned to a group of objects rather than to each object individually. Since a model can contain thousands of objects, this not only increases the speed of the modelling work but also decreases the risk of errors being made by the modeller.

It is important however, to recognise that the domains have specific uses. Various disciplines might have quite different bases for the grouping into domains. Though the methodology supports, and promotes, the existence of overlapping domains, handling of domain parameters must be done with care.

In this chapter, the principles for grouping into domains are presented by a few examples which are regarded as more or less standard procedures in geological modelling. The leading principles are the following:

- Subdivision of the rock into domains is controlled by the user of the model, i.e. the appropriate discipline group (hydrogeology, transport properties, rock mechanics, etc). The geological model will provide the rudimentary subdivisions as exemplified below.
- Each declared domain must be motivated in the model description.
- The presence of one declared domain in the model must not prohibit the existence of another domain.
- The use of domains must be flexible and respond to the accumulated knowledge, or lack thereof.

Domains based on rock distributions

Different rock types will be separated by rock boundaries in the model. The boundaries outline the smallest element in the model, the unit. For instance, in the Simpevarp area, SGU has carried out a subdivision of the ca 1800 Ma *Småland granites* into *granite-quartzsyenite*, *granite-granodiorite* and *granodiorite-quartzmonzonite* /Bergman et al, 1999/. However, if no significant difference can be demonstrated between these three granite varieties, for example, from a rock mechanical or geohydrological viewpoint, the units can be grouped into a single domain, for the purposes of those disciplines. This allows the modeller to treat the units together and increase modelling speed.

Domains can also be used for rock volumes in which the lithological heterogeneity is large and the constituent rock types have volumes too small to be practically handled. For instance, the main rocks at Äspö are different types of Småland granite, with a relatively large content of both mafic lenses and fine-grained granites in the form of small veins and irregular schlieren. The presence of fine-grained granite in this form turned out to be of great geohydrological importance at Äspö. From a hydrological point of view, it is practical to group volumes of Småland granite with a high content of fine grained granite into a domain (cf Figure 2-3).

Another parameter which may be used for subdividing into domains is the content of quartz, which governs the heat conductivity and the porosity, and hence steers the transport properties, etc.

Domains based on structure and alteration

Subdivision based on foliation

The foliation in the rock can induce an anisotropy which can influence rock strength, fracture orientations, etc, which in turn can steer the layout of tunnel systems. Though the foliation is expected to vary in intensity and direction at a site, we do not anticipate the necessity of grouping into domains unless the intensity of the fabric is considerably different in one part of the model with respect to other parts. For instance, it might be of use to create a domain corresponding to the core zone of a major ductile shear zone (cf Figure 2-2), or an area with a high concentration of small-scale ductile shears zones.

Subdivision based on fracture density and alteration

The creation of domains based on fracture density and alteration follows the principles discussed for single hole interpretation (see Section 4.2). Ideally, single hole interpretation will provide necessary input for the creation of domains in 3D.

Subdivision based on the occurrence of local minor deformation zones

Local minor deformation zones are usually too small to be described deterministically in site descriptive models but are often quite significant from a geohydrological point of view. The frequency and characteristics of such zones can be used for creating domains in which the properties, geometries and densities of the zones are used as stochastic parameters.

5.4 Information on the area's geological evolution

Comprehension of the geological processes that created an area form the foundation of the model and its description. In fact a conceptual understanding, which is the main point of modelling in the context used here, is almost impossible without knowledge of geological history. The geological history also provides means to predict the likelihood and nature of future geological events that may impact the performance of a repository.

It is, however, beyond the scope of this report to detail how the geological history should be defined. We do not anticipate the descriptions of geological evolution to differ significantly from those usually provided by SGU as part to their bedrock map descriptions. Yet, with respect to safety assessment and repository design, we emphasise brittle deformation and anticipate being able to, at least partly, describe brittle deformation of the area by absolute and relative dating of fractures /Tullborg et al, 2001/.

For communicative purposes, though, we find it practical to compact the sometimes elaborate information into a table such as Table 5-3.

Table 5-3. Tentative synopsis of the geological evolution in south eastern Sweden with focus on the Oskarshamn region.

Age (Ma)	Geological event
0.115–0	Glaciation; syn- to post-glacial fault movements?; NW-SE to WNW-ESE maximum horizontal principal stress
95–0	Alpine orogeny (central Europe); opening and spreading of the Atlantic Ocean; *brittle deformation in the cratonic Oskarshamn region as a far-field effect?*
> 250	*Latest fault movements at Äspö?* (K-Ar dating of gouge material)
295–60	Tectonic activity in the Tornquist Zone (Fennoscandian border zone); *brittle deformation in the cratonic Oskarshamn region as a far-field effect?*
360–295	Hercynian-Variscan orogeny (central Europe). *Brittle deformation in the cratonic Oskarshamn region as a far-field effect?*
420–220	Subsidence related to the development of a Caledonian foreland basin, sedimentation followed by exhumation and erosion; *brittle deformation in the cratonic Oskarshamn region?*
510–400	Caledonian orogeny; closure of the Iapetus Ocean; formation of the Scandinavian Caledonides; WNW-ESE shortening (regional compression?) followed by extensional collapse; *brittle deformation in the cratonic Oskarshamn region as a far-field effect of orogenic deformation in western Baltica?*
550	Extensive sedimentation
600	Opening of the Iapetus Ocean; *far-field effect in the cratonic Oskarshamn region?*
700–600	Peneplanation; Sub-Cambrian peneplain
900–700	Subsidence related to the development of a Sveconorwegian foreland basin, sedimentation followed by exhumation and erosion; Rifting, graben formation, sedimentation in the Vättern area; Visingsö group; *brittle deformation in the cratonic Oskarshamn region?*
1100–900	Sveconorwegian orogeny; formation of the Sveconorwegian Frontal Deformation Zone ("Protogine Zone"); WNW-ESE to E-W regional compression; intrusion of dolerites – E-W extension; *Brittle deformation in the cratonic Oskarshamn region as a far-field effect of orogenic reworking of the crust in southwestern Sweden?*
1460–1420	Hallandian orogeny; *Brittle deformation in the cratonic Oskarshamn region as a far-field effect?*
1450	Intrusion of granite (e.g. Götemar and Uthammar granites)
1610–1560	Gothian orogeny; *Brittle deformation in the cratonic Oskarshamn region as a far-field effect?*
1750–1700	Transition from ductile to brittle tectonic régime
1800–1750	Formation of transpressive, ductile deformation zones in response to c N-S to NNW-SSE regional compression under low-grade conditions. Deformation zones with NW-SE to WNW-ESE and NE-SW direction display dextral and sinistral horizontal component, respectively.
1800	Intrusion of granite-syenitoid-dioritoid-gabbroid ("Småland granite"), composite dykes
1830–1800	Regional, inhomogeneous deformation under (low)- to medium-grade conditions
1830–1820	Intrusion of granitoids; volcanic activity?
1850(–1800)	Formation of transpressive, ductile deformation zones with a dextral horizontal component of movement, in response to c N-S to NNW-SSE regional compression under medium-grade metamorphic conditions; folding of foliation in pre-1850 Ma rocks
1850	Intrusion of granite-syenitoid-dioritoid-gabbroid
1890–1850	Volcanic activity and sedimentation; regional deformation under medium- to high-grade conditions
1960–1750	Svecokarelian orogeny

6 Handling uncertainties and confidence

The term "uncertainty" can have quite different meanings in different contexts. Moreover, it is not always clear whether it concerns the receiver of information, the producer of information, or the information itself as an "objective entity". In this , it is the latter which is the focus of attention. We also advocate here the need for expressing the "confidence" in the model, or aspects thereof, as a means for communicating the model builders professional but still subjective judgements based on their understanding of the geological setting or structure being modelled. If properly communicated, we believe that uncertainties and confidence might, as an ensemble, provide sufficient additional information about the model, and data therein, that users of the model, e.g. groups dealing with safety assessment or repository design, can judge and properly address the consequences for their subsequent modelling.

To ease communication, we first provide a brief outline of the terminology of various aspects of uncertainty and confidence which are believed to be relevant to geological modelling. For a more detailed discussion of uncertainty and confidence in site descriptive modelling, see /Andersson, 2003/.

6.1 Terminology

Conceptual uncertainty

Conceptual uncertainty concerns the uncertainty originating from an incomplete understanding of the structure of the analysed systems and its constituent interacting processes. The uncertainty is comprised both of lack of understanding of individual processes and the extent and nature of the interactions between the processes.

An example in structural geology might be the conceptual uncertainty concerning whether or not a ductile deformation zone is transpressive or transtensional. The consequence of this uncertainty is that the geometry and orientation of the shear zone's constituent structures cannot be predicted at depth.

Property uncertainty

Property uncertainty concerns uncertainty in the values of the parameters of a model. Such uncertainties may be caused by, for example, measurement errors, interpretation errors, or the uncertainty associated with spatial and temporal variability. Conceptual uncertainty can cause property uncertainty.

Error, precision, and bias

Error is the deviation between an estimate and the true value. The *precision* in the prediction concerns the spread between repeated predictions. *Bias*, or systematic error, concerns the extent to which individual predictions spread evenly around the true value.

Spatial variability of properties

Most properties in geology vary in space. *Spatial variability* is not uncertainty *per se*, because it can be well recognised and understood. However, it is often a cause for property uncertainty. Conceptual uncertainty, on the other hand, might influence how the spatial variability is addressed. Therefore, due to spatial variability, conceptual uncertainty may cause property uncertainty.

Geometrical variability

Though deformations zones, for instance, often can be represented as perfectly planar in various modelling tools, it is understood that it is a necessary simplification. The location and orientation of the zone is only known at the intercepts, i.e. boreholes and, occasionally, on outcrop. This means that the uncertainty concerning the location of a zone increases with distance to the observation point.

Another aspect can be illustrated by considering the thickness of deformation zones, which can vary considerably from borehole to borehole. The amount of information from boreholes is generally insufficient to address the variability in thickness with any statistical significance. It is therefore important to obtain a conceptual understanding of the structure in question so that the thickness can be properly addressed.

Both these aspects of *geometrical variability* are coupled to the scale of the model (see below).

Scale

Scale concerns the spatial resolution of a description. For a spatially varying property, the scale is the size of the domain over which the property is averaged. Spatially varying properties will manifest different values when described at different scales. For example, using a high resolution description, i.e. at the 'small scale', intact rock and fractures would be described as individual entities but, at the larger scale, the descriptions would be combined into a 'rock mass' value. Scale should *not* be confused with accuracy or precision.

Another aspect of modelling scale concerns the geometry of the structures. It is common in modelling work to mix high resolution information, such as direct observations in boreholes, with lower resolution information such as lineament maps. Though superposition of different resolutions (cf regional vs local models) is a necessary step in the modelling work, it induces a well-known uncertainty concerning the geometry and location of structures, e.g. deformation zones, since these properties are scale-dependent. Structures can change shape and orientation, or even cease to exist, in the transition from one scale to another.

Confidence

The *confidence* in a geological model is the total assembly of motives, indications, and arguments in support of the model. However, high confidence is not synonymous to low uncertainty. If the uncertainty description is well founded, the confidence can be high in the model. Conversely, if a model description with low uncertainty has a poor foundation, the confidence in the model should be low.

Obviously, assessment of confidence is highly subjective and founded on modelling skills and professional experience.

6.2 Communicating uncertainty and confidence

With very few exceptions, most geomodelling work done to date has disregarded or isolated the presentation of uncertainty from the data. We believe that a strong coupling between the data, the model and uncertainty estimates is crucial to promote understanding of a site. However, since there are many quite different aspects of uncertainty, it is necessary to use different modes of communication that are suitable to the aspect in question.

Since the methodology presented in this paper has, to a very large degree, been implemented with the RVS system, we choose to use RVS as a metaphor, when appropriate, for illustrative purposes. In the following sections, we show, by using examples, how it is intended to handle the various aspects of uncertainty and confidence.

One might consider that showing the uncertainty in interpretation of a specific structure as additional dimensions or fields, and visualising, for example, confidence using existing geometries (e.g. deformation zones) would make it possible to communicate the degree of confidence by means of colour coding, bump- or transparency mapping, etc. Though this would promote a strong coupling between the uncertainty estimate and the data, as desired, having tested this approach, we came to the conclusion that many colleagues perceived it as counter intuitive and that any graphical manifestation of confidence must be complemented by a verbal description. In other words, we find it more useful to state the confidence in an interpreted structure or set of structures in the model description rather than in the model itself.

It is important to differentiate between the confidence in the *existence* of a structure from confidence in *assessment of the structure's properties* which must be treated somewhat differently. In this section, we only address the confidence in the existence of the structure.

Though the motives for the confidence assessment will be articulated rather elaborately in the model description, we find it practical to also condense that information into tables such as Table 6-1. Though Table 6-1 is given as a tentative example, we wish to emphasise that assessment of confidence is and will remain a subjective task. However, we believe assessments can be made credible, if the basis for the assessment is clearly stated. Not obvious on Table 6-1 is the fact that different sources of information might have quite different impacts on the confidence assessment. Direct observations of deformation zones, e.g. in cores or trenches, will almost always increase confidence in interpretation of the targeted structure. Though information density is an important factor, information quality has an even greater significance.

Table 6-1. The table shows an example of how confidence in interpretation deformation zones will be communicated in the model description. The same principles will be applied to other modelled structures, if suitable. The confidence is estimated in an integrative process where the impact of various data sources is addressed. References to reports in which the structure has been identified with a particular method are given as, for example, "P-XX-YY".

Structure	Geophysics	Drilling	Seismics	Mapping	Other	Confidence*
ZLN-001					P-02-01	0
ZLN-002	P-02-02		P-02-04 P-02-11			1
ZLN-003	P-02-06	P-02-05	P-02-03			2
ZLN-004	P-02-06	P-02-12 P-02-22 P-02-26		P-02-9		3

* 0 = not evaluated, 1 = low, 2 = medium, 3 = high.

6.3 Modelling geometric uncertainty

6.3.1 Modelling a structure with dip uncertainty

Under favourable circumstances, the dip of, e.g. deformation zones, structures which are rarely exposed on surface, might be estimated from observations on outcrop in the vicinity. Suspected zones can also be investigated by ground-based methods such as VLF. In either case, the uncertainty in the dip estimate is usually given as a range, for example, 80 +/– 15°. Though the method producing this measurement, e.g. mapping, VLF, etc, will be required to state the uncertainties in the estimates, the uncertainty can be modelled explicitly in 3D as shown on Figure 6-1. A relatively small uncertainty at

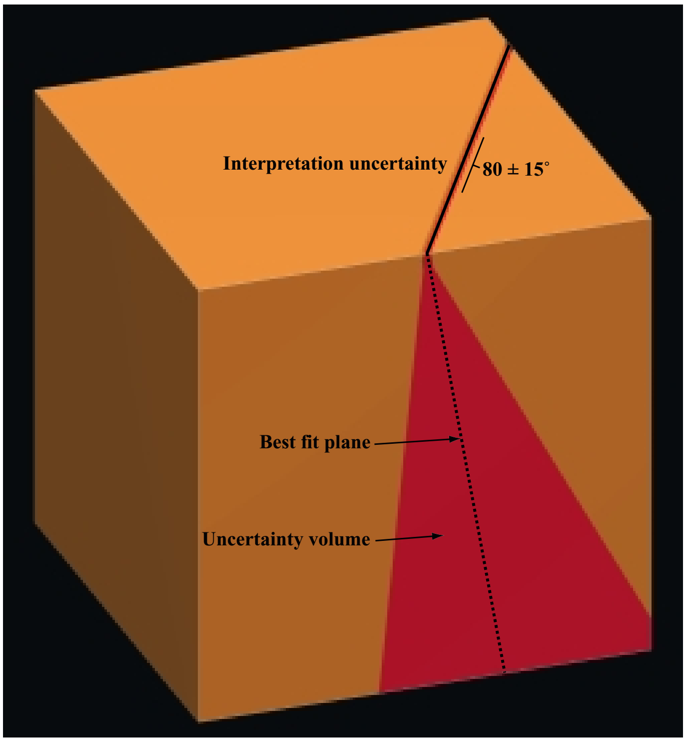

Figure 6-1. Schematic illustration of a modelled structure whose dip is given with an uncertainty range.

surface yields a quite large "uncertain" volume at depth. One advantage of this kind of explicit modelling is that volumes with low information density can be easily isolated and provide a powerful input for the planning of new investigations.

However, it is uncommon that the trace of a structure has an unambiguous position on the ground surface. An anomaly is often a more or less diffuse band and its width can be given as a confidence band. When such uncertainty in position (and in practice, in local strike) is given, the structure can be modelled in 3D as illustrated on Figure 6-2.

In addition to the explicitly modelled geometrical uncertainty as advocated above, the uncertainty in orientation, and hence position, will be given parametrically as the orientation of the pole to the best fit plane and an associated dispersion parameter (e.g. k, assuming a Fisher or Bingham distribution of dispersions from a perfect plane). The dispersion parameter is roughly equivalent to the standard deviation of the Gaussian distribution.

In the course of modelling work, the geometrical uncertainties are initially relatively large. As the site investigations advances, additional information will be acquired from, for example, outcrops and drillholes which most probably will lead to a rapid and significant reduction in geometrical uncertainty, as discussed below.

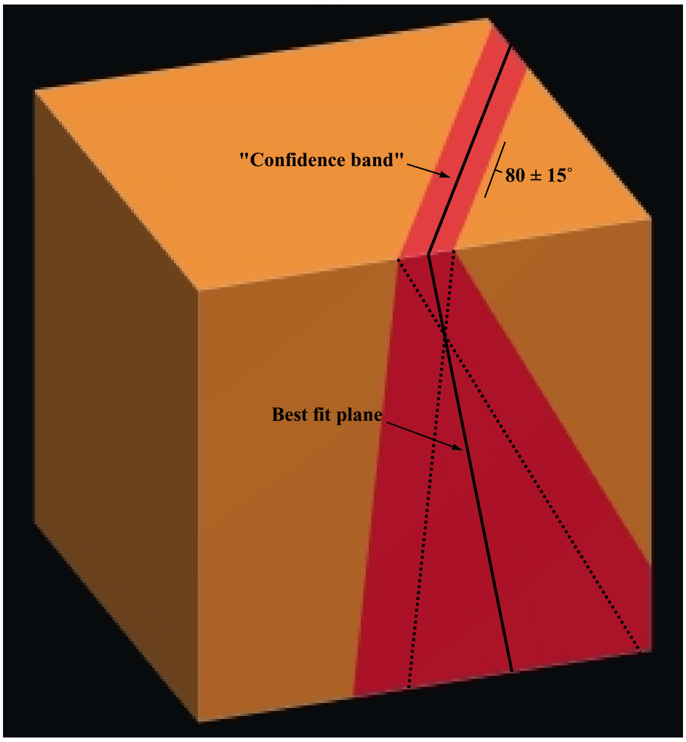

Figure 6-2. Schematic illustration of a modelled structure whose surface trace is given as a band of confidence, and whose dip is given by the same range of values as in Figure 6-1.

6.3.2 Modelling a structure with borehole intercepts

Boreholes through structures significantly reduce geometrical uncertainty, both with regard to dip and position, and with regard to thickness. How great this reduction will be is determined by distances between the borehole intersections and the surface trace of the structure. If these distances are small in a vertical direction, and the intersections are near the surface, the uncertainty in the neighbourhood of the boreholes and the surface will be small, but the extrapolation downwards will result in a relatively large uncertainty in the position of the structure at depth. On the other hand, if the distances are large in a vertical direction, and some intersections are near repository depth, there will be a relatively large uncertainty between the intersections, but the dip will be more tightly controlled (relatively small uncertainty in the position of the zone at depth). These relationships are explained in more detail in /Munier and Hermansson, 2001/ and are shown schematically in Figure 6-3.

For many purposes, it might be appropriate to define the borders of the structure as the envelope of all intercepts, as shown in Figure 6-3. The uncertainty in position of the structure can be decreased in the investigation volume of interest by careful location of additional intercepts (e.g. drillholes). Though both intuitive and practical, this approach to modelling the structures together with their geometrical uncertainties is not entirely satisfactory because the process is associated with some complications which are discussed in the next section.

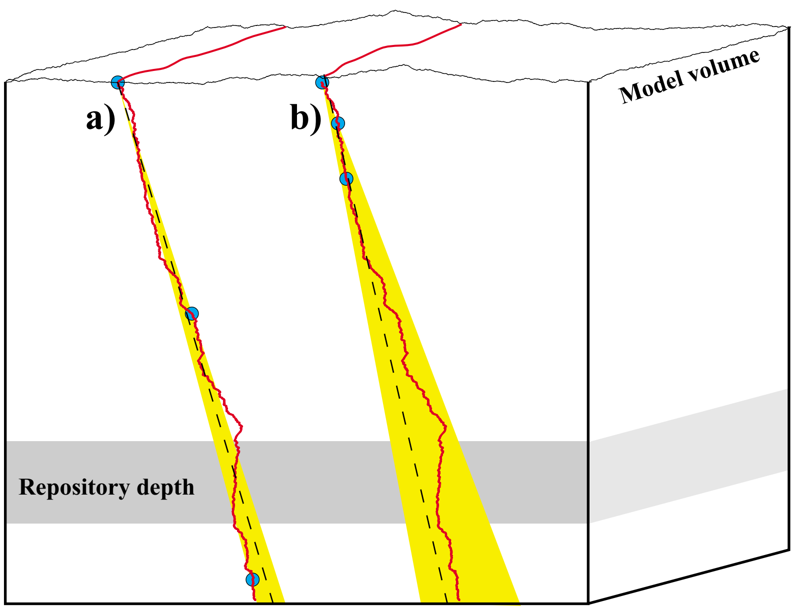

Figure 6-3. Block diagram showing how the geometrical uncertainty in the position of a deformation zone at repository depth depends on the position of borehole intersections relative to each other and relative to the surface trace.

6.3.3 Modelling an uncertainty volume – a general approach

Quite different idea of "thickness" is based on the natural undulations of the structure in 3D. Although it is not possible to determine the position of a structure over its whole area in detail, it is possible to calculate, or at least to estimate, the rock volume within which it is expected to remain (Figure 6-4) i.e. in intention, a 3D equivalent to *confidence bands* in traditional statistics though the amount of intercepts rarely, if ever, will justify a such computations. An advantage of this approach is that it is easy to define rock volumes in which deformation zones are unlikely to occur, which is important for the estimation of available volumes for the repository. The modelled geometries are also fairly simple and easy to maintain. The disadvantage is that the thickness of the modelled structure will be significantly larger than the true thickness observed in boreholes. However, honouring the observed thickness and estimating the thickness further from the observations points can be done by the procedure described below.

On the assumption that deformation zones can be treated as fractal surfaces (Figure 6-5a), it is possible to calculate the theoretically expected undulations between borehole intersections (see /Munier and Hermanson, 2000/ for details). Figure 6-5b shows a cross-section of simulations of fractal surfaces. Although the undulations can be quite large in a few cases, most of the simulations cluster around the straight line joining the observation points. By simulating a large number of planes, one can estimate the probability that the zones are located at a certain distance from the middle plane (a cross-section is shown in Figure 6-5c). Using this approach, the uncertainty volume described above can be significantly reduced using data from only a few boreholes. In fact, the simulations reduce to a simple correlation between the thickness of the uncertainty volume and the distance between observations points.

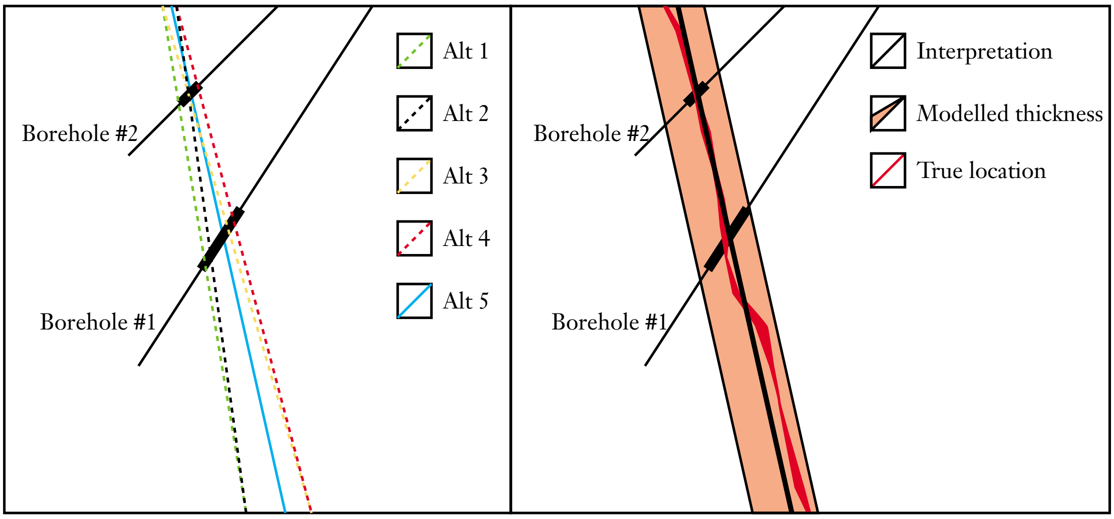

Figure 6-4. *Possible interpretations of the location of a deformation zone, given surface and borehole intercepts. The thickness of a deformation zone is modelled (right) to encompass all observations in borehole and surface and to take into consideration the natural undulation of the structure.*

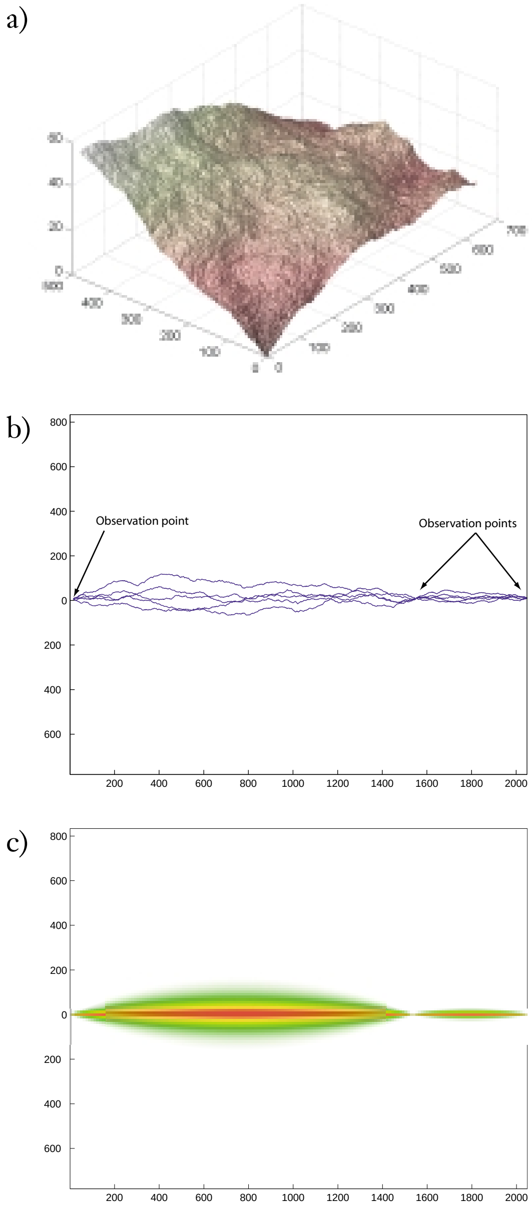

***Figure 6-5.** The treatment of deformation zones as fractal surfaces. (a) Sections through simulations of fractal surfaces between three observation points (borehole intersections); (b) Contour diagram of the probability that the generated sections are located at the indicated positions; c) Probability clouds based on realisations shown in b).*

This technique is appealing because it reflects the fact that uncertainty is small at observation points and larger at greater distances. However, it is rarely justified to adjust the modelled structures at every intersection (see example in Figure 6-6), since the process is relatively complicated, and time-consuming with regard to modelling. However, it is a practical technique, if judged necessary.

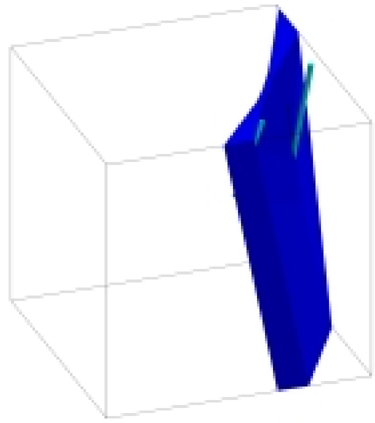

Figure 6-6. *Block diagram illustrating schematically how a structure which is modelled with its geometrical uncertainty is adjusted to take into account direct observations (intercepts) in e.g. drillholes and digged trenches.*

It is not possible to foresee future needs of detail in the modelled geometries. We nevertheless suggest, until demonstrated insufficient, that structures should be modelled as simple geometries that balance the intended overall resolution of the model with the resolution, and degree of detail, at the intercepts. The relatively simple relation between the size of a deformation zone and its deviation from a perfect plane, as argued for in /Munier and Hermanson, 2000/, allows for the construction of simple objects, such as the one illustrated in Figure 6-7.

The modelled uncertainty would then represent the volume within which the interpreted deformation zone most probably occurs. It combines the uncertainty due to natural undulation and the variation in thickness. The true thickness of the deformation zone will be given from data typically obtained from boreholes. This information will be included in the model by means of links (visualisations, in RVS terminology) to the database SICADA. Since the natural undulation is correlated to the size of the observation domain (see /Munier and Hermanson, 2000/ for detail), nestled, higher resolution submodels can be created, should a thinner modelled uncertainty be required.

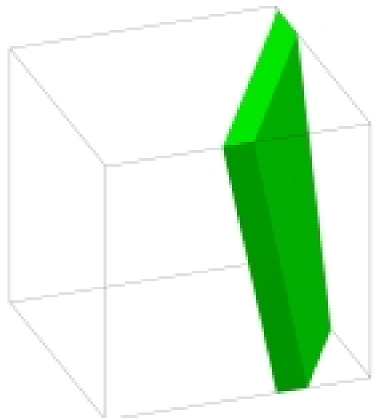

Figure 6-7. *The figure illustrates the notion of "modelled uncertainty" which is a graphical representation of calculated or estimated geometrical uncertainty.*

6.3.4 Property uncertainty

As described in Section 5.3.4, each object in the model is linked to tables of parameters that describe the properties of the modelled object. These parameters are not primary data but derivations thereof. Typically, the parameters of the models are the result of averaging several sources of primary data to yield a property representative of the modelled object at the intended resolution. For instance, the property "rock type", would correspond to the dominating rock type in the modelled object. Minor inclusions of other rock types, e.g. dikes, xenoliths, etc, will not be assigned as a property but appropriately described in the model description. Other properties, e.g. hydraulic conductivity, rock stress, etc, require extensive analyses and must be calculated elsewhere. We intend to handle the property uncertainty as follows:

Each numerical parameter of the model can be declared either as a constant, a range or a distribution. As an illustrative example, Figure 6-8 shows some of the fracture properties that can be declared. These are typically derived from analyses of borehole and surface fracture mapping, and constitute the stochastic aspect of the modelled object.

The model will not contain any information on whether the uncertainty has been derived from statistical analyses or has been estimated by expert judgement. Nor will it be possible, from the model, to obtain any information on whether stated ranges and distributions are due to natural variations (e.g. conceptual knowledge), the result of statistical analyses (e.g. averaging) or based on some judgement of uncertainty (e.g. reasonable ranges). However, the source and arguments for each property assignment will be presented in data reports, modelling reports, or the model description.

Despite the drawback that we cannot readily articulate the reasoning which leads to the assignment of uncertainty to a property, we nevertheless believe that such an estimate of the compound uncertainty should reside within the model. This to ensure that all addressed uncertainties are forwarded to subsequent analyses, i.e. to promote a strong coupling between the modelled geometries, the data and the uncertainty.

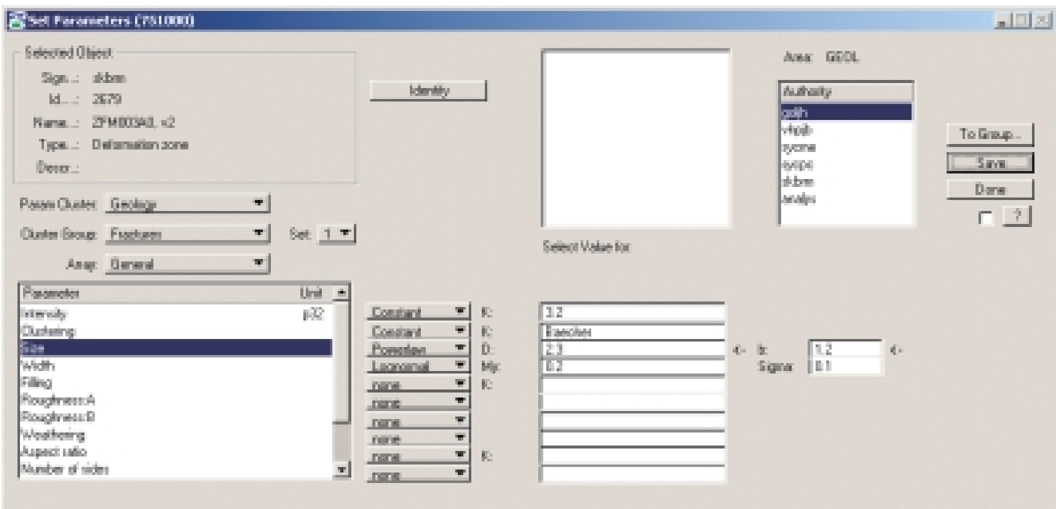

Figure 6-8. *Property uncertainty in the model is handled by the use of ranges or distributions of parameters. This example shows handling of some aspects of stochastic fracture properties.*

6.3.5 Lack of knowledge

Similar to confidence (Section 6.1), lack of knowledge is an essentially subjective entity. Though lack of knowledge may be expressed in terms of information density, this approach tends to focus on "hard" information such as boreholes, seismic profiles, etc, whereas "soft" information such as conceptual understanding of a process, empirical experience, etc, tend to gain lesser focus.

Since a considerable amount of information that forms the cornerstones of the 3D model is processed or refined from primary data, we find it essential to include, but clearly distinguish, both in the model. For example, the bedrock map, which form the basis of the rock unit boundaries (Section 4.1.4), can be regarded as a 2D model. To be able to address the issues of confidence, or lack of knowledge, users and reviewers of the model must have access to the bedrock map as well as to field notes and sampling points. The bedrock map will give information on possible sources of information whereas the field notes will show from where the information was gathered.

In fact, low confidence in parts of the modelled volume usually stems from a lack of knowledge, either due to scarcity of data or due to an incomplete understanding of the process studied. The opposite generally also holds true. We do not, therefore, anticipate the need to express the lack of knowledge explicitly by some artificial entity. Rather, we find it practical to declare our confidence in a modelled volume, as described in /Andersson, 2003/, together with all the data that has been used for the interpretation. It is, of course, equally important to declare data that has been omitted from interpretation, and to give the reasons for the omission.

6.3.6 Alternative models

There are limits beyond which uncertainties cannot be described as geometries or property distributions. For instance, it is rather meaningless to have infinite ranges on properties or too conservative estimates of dip uncertainty. Also, one might anticipate a situation in which data support for a particular structure is weak but the implications of such a structure is severe for subsequent analyses. It might therefore be necessary to formulate alternative models (Figure 6-9). The notion of alternative models covers both the aspect of alternative geometrical representations and the aspect of alternative descriptions (models such as DFN or SC (stochastic continuum), or parameter values) within the same geometrical framework.

Handling several alternative models is quite demanding because it may be difficult to challenge the modelling team to develop different alternative models in parallel. Furthermore, as models are used as input to subsequent models, a large number of alternatives may become impractical to handle.

A detailed discussion concerning alternative models is given in /Andersson, 2003/ and will therefore not be discussed further here. We wish, however, to accentuate the following:

In practice, maintaining several alternatives leads to a substantially increased workload. The amount of alternatives forwarded to subsequent analyses should be kept at a minimum. However, all alternatives need not be equally probable. In fact, the generation of alternatives is one of the ways of exploring confidence. Hence, construction of a variety of relatively shortlived alternatives is a natural *modus operandi* for the modelling team.

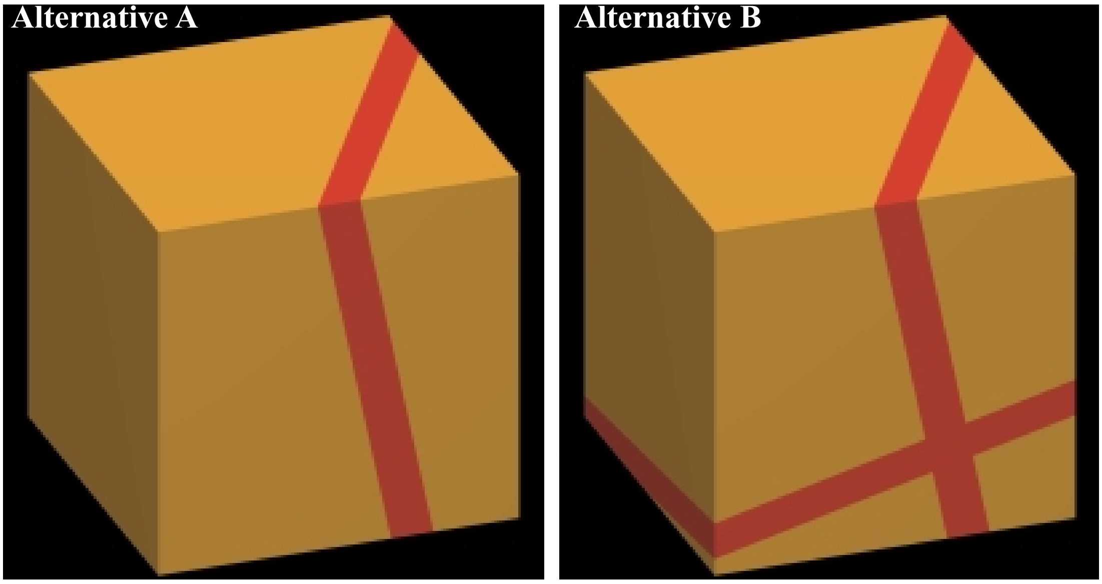

Figure 6-9. *The alternative model B contains a gently dipping zone which may considerably affect subsequent analyses.*

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Appendix A1

Brief descriptions of the main methods used for data acquisition for 3D geological modelling of sites in Swedish bedrock

A1.1 Method description classification system

An overview of the Quality Assurance (QA) of the site investigations is presented in SKB /SKB, 2000/. In short, the QA system is intended to promote SKB to do the correct work and also, equally important, to do that work correctly.

Programmes and operating plans ensure doing the correct work, while doing it correctly is ensured by Activity Plans (AP). An Activity Plan sets out how an activity is to be performed. It usually refers to a Method Description (MD) that, in turn, specifies SKB's general requirements with respect of the method of investigation concerned, the accuracy required of it, the actual way of working and data acquisition and processing.

A1.2 Summary of the geological and geophysical method descriptions

MD 120.001

Morphological data

Interpreted data from topographic maps, satellite images and aerial photographs provide the basis for lineament maps, which in turn indicate possible deformation zones. Integrative interpretation with airborne geophysical data give supporting data, particularly for the larger deformation zones.

MD 131.001

Soil mapping

The mapping of unconsolidated Quaternary deposits (soil, in the engineering meaning of the term) aims at determining the distribution and properties of the sediments which overlie the bedrock within the study area. Data from geophysical surveying and aerial photograph interpretation form an important basis for this type of mapping. The thickness of the sediments and their variation with depth is investigated by means of shallow boreholes and trenches, together with geophysics. The results are presented in the form of soil maps and stratigraphic profiles.

MD 132.001

Bedrock mapping

The method aims at investigating the distribution of rock types and rock structures by geological mapping of the outcrops within the study area. Outcrop mapping includes the determination of the rock types and the measurement and description of structural features. Rock samples are collected for petrographic analysis. The results are presented as outcrop maps and bedrock maps, with associated descriptions. A bedrock map is an interpretation of the outcrop map, with the soil removed, and is produced by integrative interpretation of the outcrop data with various geophysical data, in particular airborne magnetic data. It should be noted that fracture mapping on the bedrock outcrops is carried out using a specialised methodology, according to method description MD 132.003.

MD 132.002

Radiometric age determination

Determination of the ages of minerals and rocks is carried out mainly to provide a basis of the description of the geological evolution of an area. Radiometric methods exploit the fact that radioactive isotopes decay at a constant rate. Analysis of the contents of different isotopes in certain minerals allows, in some cases, the age of the containing rock to be determined or estimated.

MD 132.003

Detailed fracture mapping

Detailed mapping of fractures on outcrop, a complement to fracture mapping performed during bedrock mapping (MD 132.001), requires special attention concerning the geometry of the sampling domain so that sampling bias can be properly addressed. This MD concerns high resolution mapping of fractures and describes the procedures necessary to acquire parameters required by the DFN methodology. Two methods are described: Scanline mapping and area mapping.

MD 133.001

Neotectonics

The aim of neotectonic investigations is to find signs of very young movements (e.g. post-glacial faulting) in the bedrock and the overlying Quaternary sediments. With the help of aerial photographic study and field reconnaissance, an attempt is made to identify displacements in the Quaternary sediments, complemented when necessary by digging trenches for stratigraphic and sedimentological investigations. Possible young displacements in bedrock outcrops are investigated at the same time as the fracture mapping (MD 132.003).

MD 142.001

Analysis of drill cuttings

In connection with percussion drilling, ground rock fragments (cuttings) are brought up out of the borehole, together with the drilling fluid. Samples of the cuttings are taken at regular intervals for analysis. After sieving and separation, the cuttings are investigated under the binocular microscope, in order to make an approximate evaluation of the types of rock which have been drilled. This evaluation is supported by taking into account of data from geophysical borehole logging (MD221.002) and BIPS (Borehole Image Processing System, MD222.006).

MD 143.006

Drillcore mapping

Boremap is a system for mapping geological parameters, such as rock types, fractures, and zones of alteration, on drillcore. This drillcore mapping is combined with BIPS (MD 222.006) to produce core/BIPS syntheses (see Section 4-2), and then with other methods, such as geophysical borehole logging (MD221.002) and borehole radar (MD 252.020) for single hole interpretations.

MD 160.001

Petrographic analysis

In order to describe the minerals and rocks more precisely, samples are taken in connection with the bedrock mapping. Thin-sections are cut from a selection of the rock samples, in order to determine the mineral composition, which is the basis of rock classification. For the determination of the chemical composition of the minerals and rocks, X-ray diffraction and ICP spectrometry methods are used.

MD 211.002 and 211.003

Airborne geophysics

Airborne geophysical surveys by helicopter are carried out to investigate the physical properties and structure of the surface-near bedrock and the overlying Quaternary sediments (see Table 3-3). Airborne geophysical methods also yield results which contribute towards subdividing and classifying the soil and the bedrock into various sediment and rock types, as well as towards detecting and orienting structures, lineaments and deformation zones.

The different methods provide information from different depth intervals in the geosphere. In general, the resolution is greatest near the surface and decreases with depth. To generalise somewhat, the airborne geophysical systems which are available on the market today yield information from the following depth intervals, in the types of geological milieu which are being worked on by SKB:

- gamma-radiation spectrometry elucidates conditions at the surface,
- EM gives information from the surface down to between 50 and 150 m,
- magnetometry can give an impression of the distribution of rock types down to several hundred metres of depth.

MD 212.003

Gravimetry

Gravimetry is used to investigate how the gravitational field at the Earth's surface varies across a site and its surroundings. The variations in the gravitational field reflects the density distribution in the bedrock. Density varies according to rock type, depending on the mineral composition. For example, basic rocks in general have a higher density than acid rocks. Hence, gravimetry contributes information relevant to the lithological model. In particular, the technique can give indications of the presence of unsuitable rocks in the potential repository volume, which do not appear at the bedrock surface.

MD 212.004

Magnetometry

Magnetometry, using various types of instruments, is used to investigate the distribution of magnetic minerals, such as magnetite, in the bedrock. Since the content of these minerals varies between different rock types, the measurements can be used to map lithological variations. In addition, magnetite can be oxidised in fracture zones, yielding non-magnetic minerals, enabling such zones to be identified in the form of low-magnetic zones. The main aim of magnetometry is to provide input data to the lithological and structural model.

MD 212.005

Resistivity measurements

Measurement of resistivity means that the potential field which arises from the transmission of electricity in the ground is measured. Measurement can be carried out using different methods, depending on the type of problem. Resistivity measurements provide input data for structural models, since deformation zones generally have a resistivity which is less than that of the neighbouring rock. Resistivity is also capable of identifying variations in the degree of fracturing in the bedrock.

In addition, resistivity measurements provide information on the presence of concentrations of sulphide minerals and graphite. This is important because such concentrations are indications of, from SKB's point of view, unsuitable rock bodies in the repository volume. In certain situations, resistivity measurements can give an indication of the depth to groundwaters with high salt concentrations (deep brines). Resistivity measurements can also give information on soil deposits, such as the presence of silt or clay layers and their relative thicknesses.

MD 212.006

VLF (Very Low Frequency)

VLF is an electro-magnetic measurement technique which in different forms gives information on the electrical conductivity of the ground. VLF measurements, above all, provide input data for structural models, since deformation zones in general show a higher conductivity than the neighbouring rock. VLF can also give information on concentrations of sulphide minerals and graphite. In addition, VLF measurements, under special conditions and using a special form (VLF-R), provide certain information on geometrical variations or conductivity changes in Quaternary deposits. The presence of silt and clay layers improve this capability.

MD 212.007

Slingram

Slingram is an electro-magnetic measurement technique which provides information on the electrical conductivity of the ground by means of induction. Slingram measurements will mainly be used to provide input data for structural models, since deformations zones in general show a higher conductivity than the neighbouring rock.

Slingram measurements can also indicate concentrations of sulphide minerals and graphite in the bedrock. In addition, under favourable conditions, Slingram can give some information on the Quaternary deposits, above all the presence of silt and clay layers, and sometimes on the relative thicknesses of the layers.

MD 221.002 and 221.003

Geophysical borehole logging

For SKB's site investigations, it is of great importance to be able to localise fractures and to evaluate the distribution of rock types and fractured rock in boreholes. For this purpose, conventional geophysical borehole logging (often called "wireline logging") is an important technique. Geophysical borehole logs provide the basis for a "pseudo-geological" mapping of the borehole. With different tools, a number of physical parameters are determined as they are together lowered continuously down the hole, and detailed study of the logged parameters can, in many cases, differentiate between different rocks and different types of alteration. Usually, one parameter is insufficient for this and a combination of the logs of several parameters is necessary. Borehole segments of fractured rock commonly give anomalous measurements, enabling them to be identified and located. Geophysical logging can be carried out in both cored and percussion-drilled boreholes.

Logging is often carried out by combining several techniques, and probes of several types are joined for more effective work. A compilation of the most common techniques is given in Table 3-4.

MD 222.006

Borehole-wall imagery (BIPS, etc)

TV imagery of borehole walls, using BIPS, OPTV or similar instrumentation, is a method of obtaining continuous rock characterisation data and structural data along a borehole in the bedrock. BIPS-type techniques produce a continuous, digital and oriented, 360 degree colour picture of the borehole wall, which is used in conjunction with drillcore logging (Boremap, MD 143.006) for single hole interpretation.

MD 230.001

Petrophysics

Petrophysical investigations on rock outcrops and on samples in the lab provide basic data for the interpretation of geophysical measurements made from the air, on the ground and in boreholes. The measurements are used to define the physical properties of rocks, sediments and deformation zones. The properties which are determined include density, magnetic susceptibility, gamma-radiation properties and electrical properties.

MD 241.004

Reflection seismic profiling

Reflection seismic profiling is a surface-based geophysical method in which the travel pattern of seismic waves in the bedrock is used to interpret the subsurface structure. In the type of bedrock of interest to SKB, the method is used to determine the occurrence of deformation zones, and, to a certain extent, also lithological boundaries.

The seismic reflections from depth in the bedrock (down to 1–3 km) provide, together with geological information from surface mapping, drilling, VSP (see below), etc, data which can be used to interpret rock boundaries, and fracture and fault zones, both with regard to lateral extent and position.

MD 242.001

Refraction seismics

Refraction seismic surveying is a geophysical technique in which the travel pattern and velocity of seismic waves is used to determine the thickness of unconsolidated deposits (soil) and the seismic velocities of soil and bedrock. The measurement results are presented in the form of velocity profiles in which the soil structure consists of layers of differing seismic velocity. The seismic velocity is used to identify different types of sediment in the soil and to evaluate rock quality in the bedrock. Sometimes the position of the water table can also be obtained.

MD 243.003

VSP (Vertical Seismic Profiling)

VSP is a seismic method which is used in boreholes and provides a complement to surface-based reflection seismics (MD 241.004). VSP makes it possible to identify the source of the reflections registered in surface-based seismic studies, when the source is penetrated by the borehole. The method can also detect and localise shallowly dipping reflectors lying underneath the borehole, as well as steeply dipping ones outside the borehole. Furthermore, it allows the vertical velocity profile of seismic waves in the subsurface to be accurately determined, to the advantage of the processing of the data from surface-based reflection seismics.

MD 251.003

Ground Penetrating Radar (GPR)

GPR is a geophysical technique which uses the travel pattern and velocity of electromagnetic waves to determine the depth, structure and electrical permitivity of unconsolidated deposits (soil), and the position of the groundwater table. If soil is thin or absent, the technique can also be used to detect surface-near fractures and fracture zones in the bedrock. The application of the technique is strongly dependent on the clay and silt content of the soil, since high contents reduce the distance of penetration.

MD 252.020

Borehole radar

Borehole radar is a geophysical technique for localising and determining the orientation of structures in the bedrock, such as fractures, fracture zones, crush zones and lithological contacts, which are penetrated by, or occur in the vicinity of, a borehole.

During logging with this technique, a transmitter in the borehole emits an electromagnetic pulse into the surrounding bedrock. Structures with divergent electrical properties act as reflectors for the radar waves, and the reflected energy is registered by a receiver in the borehole. Measurements can also be made between boreholes, or between borehole and ground surface (so-called tomography), whereby velocity variations in the radar waves can reveal, for example, fracture zones within the studied rock volume.

MD 260.001

Marine geology

Marine geological investigations in the present context consist of acoustic geophysical methods and sediment sampling by simple methods (e.g. dredging or shallow drilling). The information obtained allows the sediments to be classified and the geometry of their distribution to be determined. The morphology of the sea floor and the bedrock surface is also obtained.

A1.3 References

SKB, 2000. Geoscientific programme for investigation and evaluation of sites for the deep repository. SKB TR-00-20, Svensk Kärnbränslehantering AB.

Appendix A2

Statistical analysis of fracture data, adapted for Discrete Fracture Network (DFN) modelling

A2.1 Introduction

The possibilities of deterministically fixing the geometry and properties of individual fractures in a large-scale model are extremely limited. Hence, a statistical treatment is used to describe fracture systems in rock bodies. The fracturing is described with DFN (discrete fracture network) parameters, which define the directions, and spatial distribution of the fractures, as well as other characteristics such as mineralogy or transmissivity.

RVS models, and their inherent DFN parameters, can afterwards be used, in DFN codes specially developed for that purpose, for understanding how the fractures influence, for example, stability, flow and transport in and through the rock mass.

Information from outcrops and boreholes provide the basic data for defining the DFN parameters. These data, however, must go through an extensive processing before they can, in a correct way, simulate the properties of natural fracture network.

A2.2 Purpose

The present appendix describes the DFN parameters which are necessary for RVS modelling, the way in which they are extracted from the data base acquired during site investigations, and their assignment to geometrical objects in the model. The purpose here is to present a clear methodology for calculating and assigning DFN parameters to objects in RVS models. The methodology is designed to facilitate subsequent DFN modelling with other tools.

A2.3 DFN parameters

In order to create a fracture network, the following minimum amount of information is required:

- orientation of the fractures,
- size of the fractures,
- fracture intensity,
- fracture termination (how fractures cross each other),
- the spatial distribution of the fractures (the fractures relative position in space, correlation).

This information is preferably given as different distribution functions with their moments. These can vary within the same model.

The other parameters of interest for DFN modelling, such as mineralogy, water-conducting properties, rock mechanical properties, etc, are not treated here. Such parameters can be determined using conventional tools, if necessary, and, together with the geometrical aspects of the DFN parameters described here, can be used as a basis for more or less complex DFN models for different uses and users.

In the present section, we give a brief description of the geometry-related parameters and of the way in which the distribution functions are determined. The analysis of fracture statistics is a wide scientific subject area, and there exist many more analysis methods than those presented below. The methodology presented here is judged to be sufficient to give the necessary background to the DFN models which will be used during the site investigations.

A2.3.1 Orientation of fractures

Fractures in the bedrock are rarely oriented in a random fashion. Often, one or several dominating orientations occur, called *fracture sets* (see, for example, /Stråhle, 2001/ for nomenclature). The *fracture matrix* (sprickmatris) consists of all the sets, which occur in the rock mass, and their properties. The most natural first step in modelling is therefore to identify the fracture sets which make up the fracture matrix. There are two methods of achieving this: the visual method, and the numerical method. However, before the mean orientation of the fracture sets can be determined, the data must be corrected for a distortion introduced by the fact that 3D fracture populations are normally sampled on planes (outcrops) or lines (boreholes), as explained in the next section.

Terzaghi correction

When one maps gently sloping outcrops, most of the fractures measured are steeply dipping. Gently dipping fractures are going to be under-represented, since the probability that such a fracture will intersect the surface is less than of that of steep fractures. Similarly, the fractures in a fracture set which intersects a borehole at a low angle are going to be under-represented with respect to those in a set which intersects at a high angle.

There are, however, a number of methods for handling this observational error, and these are mainly based on the so-called *Terzaghi correction* /Terzaghi, 1965/. Briefly, the correction is aimed at compensating for the under-representation by weighting each fracture according to the angle between it and outcrop surface or borehole axis.

How significant the Terzaghi correction is depends on the characteristics of the fracture matrix, variations in the shape of the outcrop surface, the number and orientations of the boreholes, etc. Hence, it is not possible to give general recommendations on the application of the correction factors. Since the application of the correction factors can significantly affect the interpretation, it is very important that the correction method be clearly described in each individual case.

Identification of fracture sets

An important tool for the description and analysis of fracture orientation is the stereonet, which is in principle a three-dimensional protractor. Diagrams which consist of data plotted using the stereonet are generally referred to as stereograms. With the help of the stereonet and stereograms, nowadays mainly in their computerised forms, the mean orientation and distribution function for each fracture set can be determined. For visualising and analysing fracture data, the stereonet most commonly used in structural geology is the Schmidt net, which is an equal-area projection. The orientation data from the individual fractures (dip/strike, or dip/dip direction) can either be plotted as great circles or as poles (plane normals). For large amounts of data, and for fractures in general, it is usual to plot the fracture poles, since, otherwise, it is difficult to visually identify fracture sets.

Fracture sets can be visually identified on fracture pole stereograms by observing the positions of pole *clusters* (Figure A2-1a). Different contouring methods /Starkey, 1977; Lewis and Gray, 1985; Robin and Jowett, 1986; Adam, 1989; Vollmer, 1993, 1995/ can facilitate the identification of different fracture sets by eye, and, at the same time, can provide a basis for evaluating whether a pole concentration is statistically significant (Figure A2-1b). Of the standard methods available for contouring normals which are found in the literature, those which are based on the early work of /Kamb, 1959/ are preferred /e.g. Robin and Jowett, 1986; Vollmer, 1993, 1995/. This is because these use the spatial orientation of the normals rather than the projected position of poles in the stereogram as a basis for data processing, thus making it possible to compare different projections on a statistically correct basis.

The example in Figure A2-1 shows that it is relatively easy to visually identify pole clusters on a contoured stereogram, given, of course, that the orientations are not random and that the number of observations is sufficient. However, one can influence the sensitivity of the contouring by one's choice of contour interval, so that the number of pole clusters can vary, which introduces a certain amount of subjectivity. It is not possible to give any general rules about how the algorithm should carry out the contouring, since the result of the contouring is dependent on the number of observations, the distribution of the data, the sensitivity, etc. Hence, it is very important that the contouring method and the parameters used are stated when describing stereonets or interpretations based on them, and that the same contouring method is used throughout in one and the same model.

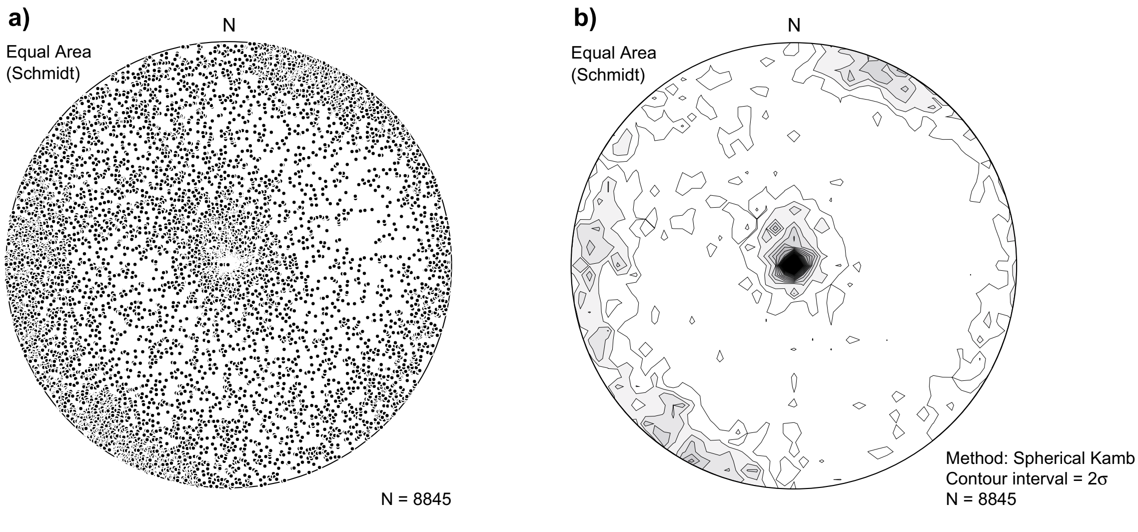


***Figure A2-1.** Fracture data from Äspö HRL. (a) Equal area/lower hemisphere stereogram of poles to fracture planes. (b) The same stereogram as (a), contoured according to the Kamb method (contour interval 2sigma)*

A large number of methods have been published which, in a more objective way, help the modeller to identify fracture sets on a stereonet /e.g. Shanley and Mahtab, 1976; Miller, 1983; Mahtab and Yegulalp, 1984; Schaeben, 1984; Kohlbeck and Scheidegger, 1985; Huang and Charlesworth, 1989; Vollmer, 1993, 1995/. It is difficult to recommend a particular one of these methods, since, in our opinion, they all have both advantages and disadvantages. Taking into account the uncertainties in the fracture orientation measurements, due to measurement errors, inadequate exposure, etc, the differences between the methods are thought to have relatively little significance for the present area of application. However, it is important that the same clustering method be used throughout the modelling work.

Many methods for set identification /e.g. Pecher, 1989/ are based on the user or the code starting with an initial evaluation of the number of pole clusters visually identifiable in the contoured stereogram and the approximate orientation of the mean of each cluster. The algorithm then attempts to decide, by systematically working through all the data, whether a particular pole with a certain statistical significance can be regarded as belonging to one or other of the pole clusters (sets). An example of the result of such an algorithm is shown in Figure A2-2.

The identification algorithm, however, is only apparently objective. As the example in Figure A2-2 shows, the algorithm assigns all data points uniquely to one of the pole clusters (sets). This is, of course, impossible, since the pole clusters (sets) are overlapping (by definition). In other words, the algorithm can contribute to assessing to which pole cluster (set) a data point *presumably* belongs and to recognising that the assignment to a cluster is always associated with some uncertainty. Sometimes, it is possible to obtain clarification from other geological information, such as fill minerals, relative age, etc but such cases are generally fortunate exceptions.

The advantage of the use of a clustering algorithm is that the mean orientation of the fracture sets are always calculated in same way and that this process can be carried out consistently within a study area with many sampling points (outcrops, boreholes, etc). Also, a measure of the density (dispersion) of each set is obtained.

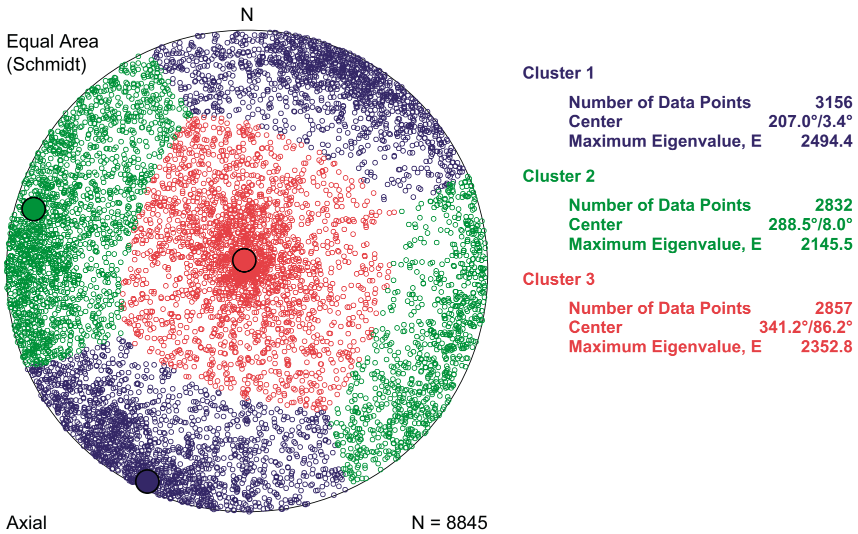


Figure A2-2. *Fracture data from Äspö HRL. Visual inspection of the contoured diagram (Figure A2-1b) suggests the presence of 3 pole clusters, one with a subvertical lmean pole and two with sub-horizontal mean poles, oriented WNW-ESE and NE-SW. Using these visual estimates, the algorithm /from Pecher, 1989/ assigns each data point to one of the three sets, and calculates the mean orientation and the maximum eigenvalue, E, of each set.*

Determination of the distribution and its moments

The identification algorithm for fracture sets, discussed above, is mainly used to separate out the data belonging to each set from a fracture matrix with several sets. The next step in the process is to analyse each set separately in order to determine a representative distribution function in terms of a mean orientation (expected values, mean) and dispersion about the mean (e.g. variance).

The poles to a fracture planes are often referred to as "normal vectors", but they are not vectors in the strict meaning of the word, they are axes. There are a number of distribution functions which can describe fracture orientation. The most common ones are the Dimroth-Watson /Watson, 1966/, /Bingham, 1964/ and /Fisher, 1953, 1987/ functions. Of these, the Dimroth-Watson and the Bingham functions are defined for axes, whilst the Fisher function is defined for vectors.

The calculation of the eigenvector and eigenvalue of the axes gives directly the mean orientation and a measure of the dispersion. It is also possible to use Fisher statistics to calculate the mean vector and the dispersion, κ (kappa), on condition that the fracture set is first rotated so that the mean fracture plane of the set is horizontal. If this is not done, the mean orientation according to the Fisher method will be incorrect /see, e.g. Davis, 1986/, since Fisher statistics is intended for vectors, not axes.

Using different statistical tests /e.g. Hext, 1963; Giné, 1975; Woodcock and Naylor, 1983/, one can test which of the distributions best fit the observed data. In practice, however, it is rarely necessary, since the measurement errors, the natural variations in orientation and the complexity of geological formations, etc makes it impossible to choose one distribution in favour of another. On the other hand, it is important that the distribution is clearly stated in the description, with the mean orientation as well as the dispersion, independent of whether it was calculated with the aid of the eigenvalue method, Fisher, Bingham or Dimroth-Watson statistics. The orientation of the different fracture sets can thus be expressed mathematically as distribution functions with moments, which afterwards can be used as parameters in a DFN model.

The Fisher distribution of vectors which are symmetrically distributed about the vector resultant can be expressed as:

$$f(\theta)=\frac{\kappa \cdot \sin\theta \cdot e^{\kappa \cdot \cos\theta}}{e^{\kappa}-e^{-\kappa}} \qquad \text{A-1}$$

where θ is the angle of divergence from the resultant vector, in degrees, and κ is the dispersion. An estimate of the dispersion factor, κ, is obtained from the relation /Fisher, 1953/:

$$\frac{e^{\kappa}+e^{-\kappa}}{e^{\kappa}-e^{-\kappa}}-\frac{1}{\kappa}=\frac{|r_n|}{N} \qquad \text{A-2}$$

where r_n is the resultant vector and N the number of vectors.

It can be shown that, for a large value of N, the estimation of κ can be simplified to /Fisher, 1953/:

$$k \approx \frac{N}{N-|r_n|} \qquad \text{A-3}$$

An example of the application of these statistics is shown in Figure A2-3. A comparison with Figure A2-2 shows that the overall pattern of fracture poles are similar, which of course is expected, but also that the clusters overlap.

Shape of the pole cluster

In crystalline bedrock, the most usual situation is that the fracture poles are symmetrically distributed about the mean pole, thus forming a roughly circular pole cluster on a stereogram (for example, cluster 1 on Figure A2-2), However, situations do occur, mainly in sedimentary rocks, in which the fracture poles are distributed asymmetrically (in an ellipse rather than a circle) about the mean pole.

There are a number of methods of investigating and quantifying the degree of asymmetry, of which those of /Vollmer, 1989/ and /Woodcock, 1977/ (Figure A2-5) are most commonly used. Both methods are based on different aspects of eigenvectors and eigenvalues (Figure A2-4), and both are equally relevant and give similar information, when applied to fracture statistics.

If the deviation from a regular cluster shape is significant, the pole cluster should be defined using the bi-modal types of the Fisher /Fisher et al, 1987/ or the Bingham distribution /Bingham, 1964/. The estimation of the dispersion, κ, then becomes much more complicated since κ varies in different directions about the mean pole. Instead of a single measure of the angular variation from the mean pole (cf Equation A-1), two dispersions, κ1 and κ2, are given, along the two vectors, which define the axes of the elliptical pole cluster.

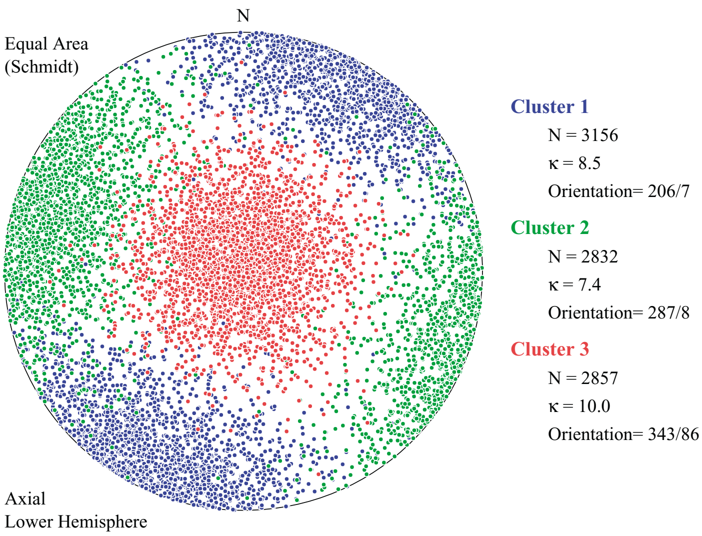
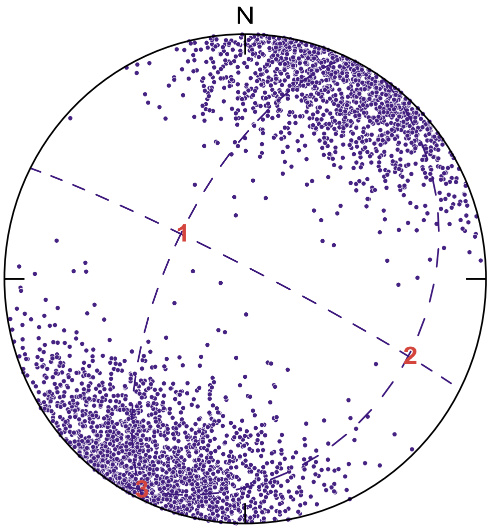


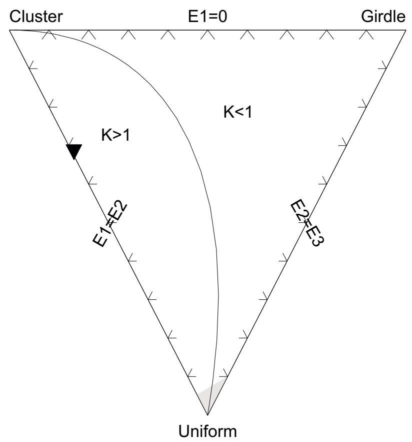
Figure A2-3. *Simulated fracture orientations based on the data shown in Figure A2-2.*



Principal Directions

Vector	Trend	Plunge	Value
1	304	63	330.05
2	115	26	339.59
3	207	4	2486.36

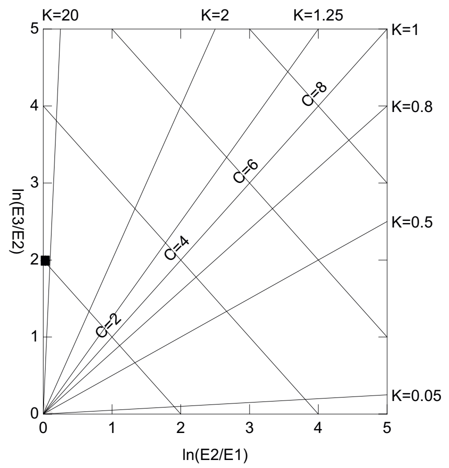
Figure A2-4. *Example of the calculation of the centre of gravity of a pole cluster using eigenvectors. In addition to eigenvectors, which indicate direction, the inherent properties of eigenvalues can be used to analyse the cluster's shape (Figure A2-5).*



Vollmer's Fabric Indexes

Index	Value	St.Dev.
Cluster	0.680	0.000
Girdle	0.006	0.000
Uniform	0.314	0.000
Cylindricity	0.686	0.000

Non-uniform distribution.
Tested at the 95% confidence level.



Woodcock Ratios

Ratio	Value	St.Dev.
K ratio [ln(E3/E2)/ln(E2/E1)]	69.914	1.692
C ratio [ln(E3/E1)]	2.019	0.001

Critical C value = 0.16
Moderately developed unixial cluster.
Tested at the 95% confidence level.

Figure A2-5. *Illustration of two statistical methods for analysing the shape of pole clusters: the method of /Vollmer, 1989/, on the left, and the method of /Woodcock, 1977/, on the right. The plots show that the analysed cluster is conical (circular on a stereogram) and that the fractures show relatively little dispersion about the mean orientation. In both methods, E1, E2 and E3 are the same as in Figure A2-4.*

A2.3.2 Fracture size distribution

A fracture trace is the intersection between a fracture and a mapping surface, such as an outcrop, a tunnel wall, or a road cut. Fracture trace length is a measurable quantity, but is only the length of the intersection between the fracture and observation surface. However, a fracture is really a three-dimensional structure, which has a size that can be expressed as an area, or, with certain assumptions, as the radius of the circle which has a corresponding area. For DFN purposes, it is important to know the size distribution of the fracture population, since the fracture network is to be simulated in 3D.

It is not possible to measure the size of a fracture directly: for this, one would need to expose the whole fracture. In practice, this is only possible for fractures of very limited size. For all practical purposes, the analysis of fracture size distributions must be based on fracture trace statistics.

The mapping of fracture traces is in turn subject to several sources of error, associated with the "cut effect" (i.e. fractures at a low angle to the mapping surface will be under-represented relative to fractures at a high angle) and the "window effect" (i.e. the terminations of larger fracture traces will often lie wholly or partly outside the sampling window, e.g. outcrop). These effects can be handled using a variety of methods, as set out, for example, in /Priest, 1993/. Fracture trace statistics can be used to facilitate the identification of pole clusters, but the most important area of application is as a basis for estimating the size distribution of fractures and their spatial distribution.

Using a DFN tool /e.g. Dershowitz et al, 1995/, one can simulate an artificial fracture network and create a fracture trace population by cutting the network with an artificial sampling surface with the same geometry as the actual mapping domain. The fracture trace statistics of the simulated sampling surface is then compared with that of the mapped surface, and, in an iterative process, an acceptable similarity is approached by altering successively the distribution functions of the artificial network. Similarities and differences can be quantified and tested using, for instance, Chi-Square or Kolmogoroff-Smirnov convergence criteria. For the iteration, different search algorithms can be used to find the best fit to a given natural distribution, such as the "simulated annealing" /Kirkpatrick et al, 1983/ or "conjugate gradient" /Hackbusch, 1985/ methods.

An alternative method to estimate fracture size distributions is based on fractal geometry /King, 1992; Korvin, 1992; Barton and La Pointe, 1995/. By studying fracture trace data at different scales, from regional lineaments to outcrop cracks, it is possible, with certain assumptions, to directly estimate the moments of a power-law (also called Pareto) distribution.

If there are grounds to believe that the fracturing in a rock mass is independent of scale, one can, by making certain assumptions, use the cumulative distribution function (cdf) of a power-law distribution, which is defined as follows:

$$F_X(x) = 1 - \left(\frac{c}{x}\right)^a, \qquad a \le x < \infty, \quad a > 0, \quad c > 0, \qquad \text{A-4}$$

and the corresponding probability distribution function (pdf) is:

$$p_X(x) = \frac{c \cdot a^c}{x^{c+1}} \qquad \text{A-5}$$

where:

- parameter **x** describes the fractures size, expressed as the equivalent radius of a circle of corresponding area,
- parameter **a** is usually called the position parameter (in practice the smallest fracture size considered), and
- parameter **c** describes the shape of the distribution.

For fracture analysis, it is more practical to use the cumulative complementary distribution function (ccdf), expressed as:

$$G_X(x) = \left(\frac{x_0}{x}\right)^a, \qquad a \le x < \infty, \quad a > 0, \quad x_0 > 0, \qquad \text{A-6}$$

which defines the probability that size X of a fracture is equally large or larger than **x**, given a smallest fracture size $\mathbf{x_0}$.

The mean value of the power-law distribution, (***μ***), is expressed as:

$$\mu = \frac{c \cdot x_0}{c-1}, \quad c > 1 \qquad \text{A-7}$$

Yet, the distribution which best describes *fracture trace length* is usually the log-normal distribution. However, this does not mean that this type of distribution necessarily best describes the *size* (equivalent radius) of fractures. Theoretically one can show that a fracture network with a power-law distribution of equivalent radii, when it is intersected by a plane, results in a log-normal distribution of fracture traces on the plane. In practice, this means that it is necessary to test which distribution best fits the observed data, for example with a Chi-Square or other test. In the model description, therefore, it must be stated which distribution was tested, the results of the test, and other reasons for the choice of the size distribution.

A2.3.3 Fracture intensity

Fracture intensity is often also called fracture density or fracture frequency. Intensity can be measured in terms of the number of fractures per metre along a measurement line or a borehole, in which case it is a one-dimensional parameter. In DFN methodology, this parameter is usually called P_{10}, where the subscript 1 stands for the dimensionality and subscript 0 for the measurement unit (here, a number, i.e. dimensionless).

Fracture intensity can also be given as the total length of fracture trace per unit area, which one has measured on an outcrop surface of a certain area. In this case, the parameter is two-dimensional and is called P_{21} (dimensionality – 2, measurement unit – length).

Fracture intensity can also be expressed as the total area of fracture within a unit volume of rock and is then designated P_{32} (dimensionality – 3, measurement unit – area).

In order to describe fracture intensity, it is desirable to use a term which is independent of scale or direction. P_{10}, for example, varies with the orientation of the measurement line, and P_{21} is dependent on the orientation of the surface being mapped, when the fracture matrix, as is normal in natural fracture systems, is made up of a number of different sets. P_{32} , however, is independent of scale or orientation and is therefore an attractive way of describing fracture intensity. Unfortunately, P_{32} cannot be measured directly in the field. However, a relation of proportionality exists between P_{10}, P_{21} and P_{32} which can be used to calculate P_{32} from measurements of P_{10} (e.g. borehole data) and P_{21} (areal outcrop data).

The following methodology can be used to calculate P_{32} from observed P_{10} or P_{21}. The method requires that one has already characterised the orientation and size distribution of each fracture set:

1. Generate a fracture network with a guessed fracture intensity P_{32mod}. There is no special criterion for the value used except that it should be greater than the true value of P_{32}.
2. Sample the DFN model with artificial boreholes and artificial outcrops with the same orientation and size as the real ones.
3. Calculate the fracture intensity parameters for the sampled boreholes and surfaces (P_{10mod} and/or P_{21mod}).
4. Calculate the $P_{32field}$ using the formula:

$$\frac{P_{10field}}{P_{10mod}} = \frac{P_{21field}}{P_{21mod}} = \frac{P_{32field}}{P_{32mod}} \qquad \text{A-8}$$

The fracture intensity has great significance for the understanding of degree of fracturing in the rock mass and affects, therefore, the rock's hydrogeological and rock mechanical properties, together with the orientations and size distributions of the fractures.

Another problem with P_{21} is that the size distribution is distorted by the fact that the intersecting surface does not always – in fact, does very rarely – cut the fracture through its midpoint. There is practically never a direct relation between the fracture trace length on the surface and the size defined as the equivalent circle radius. The above procedures does not take this effect into account. However, using bootstrap procedures such as those described in e.g. /Dershowitz et al, 1995/ and applying Equation A-6 will yield a correct estimate of P_{32}.

A2.3.4 Statistical evaluation of the spatial distribution of fractures

Fracture and lineament maps can look different even though the orientation, size distribution and intensity parameters are similar. Fracture traces, for example, can be evenly distributed over the mapped surface or can be concentrated in different groups, or swarms, unevenly.

Several types of spatial distribution models exist in order to describe 3D fracture distributions or "patterns". A fracture network with a spatial distribution of fractures according to the Baecher model /Baecher, 1983; Geier et al, 1988/ corresponds, in principle, to a Poisson distribution of fracture trace midpoints over an observation surface.

The Nearest Neighbour model /Geier et al, 1988/ is coupled to an increase of fracture intensity around the larger fractures, which can be an applicable model to simulate, for example, fracture zones and the increased degree of fracturing which is found near larger structures.

The Levy-Lee fractal model /Geier et al, 1988/ describes the distribution of fractures in space using a fractal behaviour, and is characterised by a Levi Flight fractal process to produce clusters of minor fractures around larger, more evenly distributed fractures.

Other, more geologically argued, spatial distribution models exist, which are coupled to deterministically located boundary structures. These are based on, for example, fold models, fracture zone models, etc, whereby it is other parameters, which determine the location, orientation and size of the fractures. However, with this methodology, it is of great importance to show how the analysis of spatial distribution was carried out on the basis of the observed fracture data.

Below, three types of analysis for spatial distribution are suggested in order to determine which distribution model is most suitable for the observed fracture system. The Baecher analysis and the Nearest Neighbour analysis both use the same principle, whereby the outcrop map is subdivided into grid cells, within which the number of fractures and the fracture intensity are calculated. The Levy-Lee analysis is based on the subdivision of the outcrop into circular domains and is most suitable for scale-independent fracture data.

Baecher analysis

The Baecher analysis calculates the fractal dimension, based on the size of the cell, and uses a Chi-Square test and a correlation coefficient to calculate the statistical significance of fit of the observed data set to a stationary Poisson point process.

The analysis is carried out by placing different grid nets over the fracture map (Figure A2-6), whereby the number (and therefore, size) of the grid cells is varied. For each grid net, the number of fracture trace centres which occur in each cell is counted. In order that the analysis is statistically significant, there need to be at least 2 fracture traces in each cell.

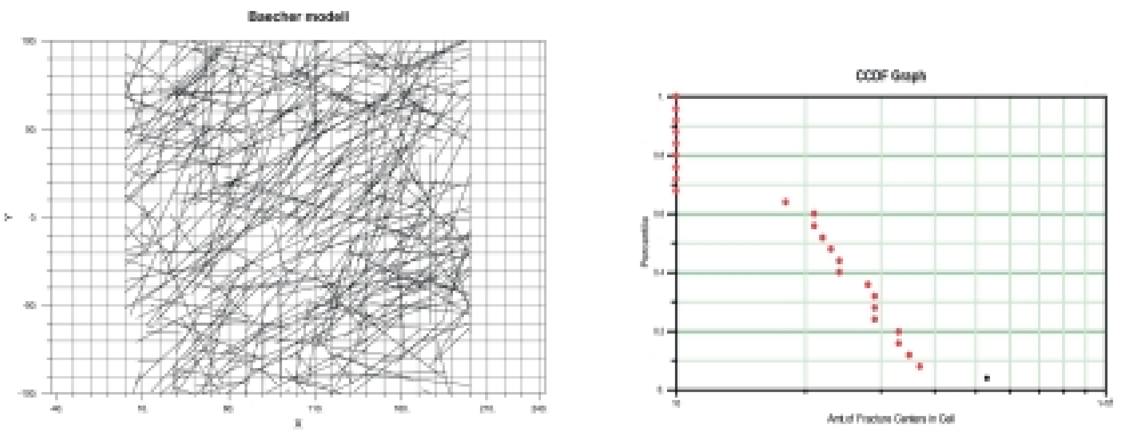


Figure A2-6. *Analysis of spatial distribution of fracture traces on an outcrop surface according to the archer method /Baecher, 1983/.*

The total number of fracture traces in each cell is plotted against the inverse of the cell size. The curve so produced can be related to the fractal dimension. A dimension close to 1 is indicative of a very heterogeneous data set, i.e. the fracture traces occur in groups over the surface whereas a dimension close to 2 is indicative of a statistically homogeneous distribution across the surface.

Nearest Neighbour analysis

The Nearest Neighbour method analyses how fractures are localised in the surroundings of large fractures. The theory states that fracture intensity decreases exponentially as the distance (x) from major fractures increases.

The analysis calculates the relation between fracture intensity, P_{21}, and the distance between deterministically defined major fractures. A Chi-Square test and a correlation coefficient indicates the level of significance of the hypothesis that the observed fractures can be described with a Nearest Neighbour model.

Levy-Lee fractal analysis

The Levy-Lee fractal method is based on the probability that the distance between fracture traces follows a power-law distribution which is defined by:

$$P_{Ls}\left[L > Ls\right] = Ls^{-D} \qquad \text{A-9}$$

where D is the powerlaw exponent of the fracture centres, and Ls is the distance between two consecutive fractures in the generation process. D = 0 represents a fracture map which is statistically homogeneous. The larger D becomes, the more closely grouped (statistically heterogeneous) are the different sets of fractures.

The powerlaw exponent, D, is calculated by placing circles of different radius, but the same centre, on the outcrop map (Figure A2-7). The circle radius is then plotted against the number of fracture trace mid-points (centres) which fall within the circle. The result can be converted into a powerlaw exponent D for how the fractures are distributed in space.

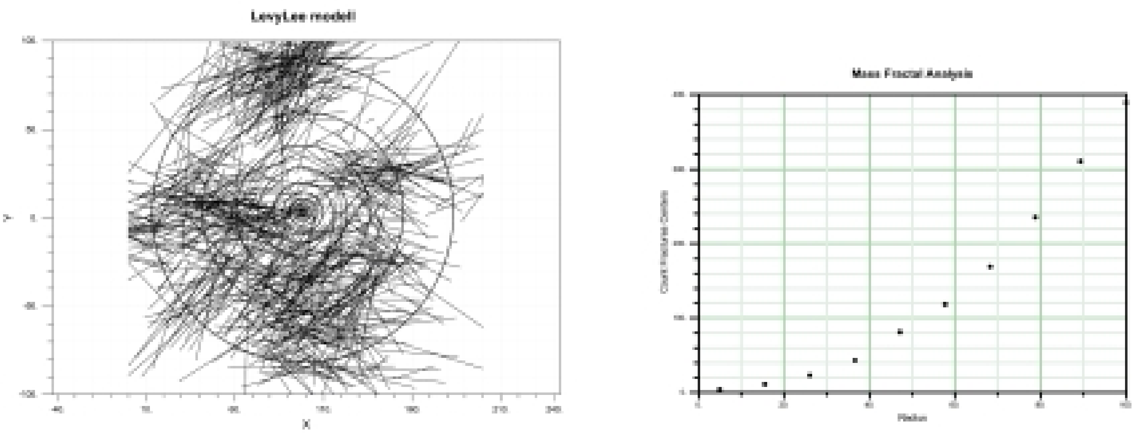


Figure A2-7. *Analysis of spatial distribution of fracture traces on an outcrop surface according to the Levy Lee method /Geier et al, 1988/.*

A2.3.5 Termination of fractures and other fracture data

Fracture terminations yield information on the relative ages of fractures and the mechanics of fracturing. In DFN models, different types of termination can be used in the stochastic generation of fractures. If several fracture sets are defined, one can direct the stochastic realisation process to, for example, make a certain percentage of fracture set 2 to terminate against fractures of set 1, according to the observations made in the outcrop and on the outcrop map.

Termination data are not necessary in order to generate a DFN model, but they give a very good basis, if the model is to be used for rock mechanical or hydrogeological simulations.

Fracture mineralisation, roughness, fault gouge, etc, are examples of other types of fracture data which are important, but these are not necessary for the geometrical analyses adapted for DFN. It is often important to study the coupling between purely geometrical properties in the fracture matrix and geological indicators, for instance, whether size is related to some special mineral, etc. However, this type of study is not carried out according to an established methodology, but rather requires that the data be processed from several different points of view.

A2.3.6 Result of geometrical fracture analysis for DFN applications

After having been statistically processed for DFN modelling, as outlined above, the fracture data should be incorporated in the RVS model in the appropriate fields on objects in the block model.

For obvious reasons, the statistical processing will be carried out mainly on outcrop and borehole data within rock units and rock domains outside the deterministically identified deformation zones. However, it is important that also fracture data from the deformation zones should be processed using the same methodology, in order, also here, to provide a basis for DFN models.

In addition to being fed into RVS, the DFN parameters, which resulted from the statistically processing, should be summarised in an overview table (e.g. Table A2-1), which should be referred to in the model description. Furthermore, reference should be made to the report which describes how each parameter was determined, with which tools, and according to which statistical model.

Table A2-1. Example of a summary table for DFN parameters.

Parameter	Used data				Data from	Reference
Orientation	Set	Strike	Dip	K	Pilot and Exploratory holes	This report
	1	219.0	83.7	4.84		
	2	127.0	84.2	8.35		
	3	20.6	6.0	8.33		
Size	Set	Mean (μ)	Std dev (σ)		TBM tunnel	/Follin and Hermanson, 1996/
Lognormal distribution	1	2	2			
	2	8	2			
Intensity	Set	P_{32}			TBM tunnel	/Follin and Hermanson, 1996/
	1	0.42				
	2	0.34				
	3	1.2				
Spatial model	Poisson distributed Enhanced Baecher model				TBM tunnel	/Follin and Hermanson, 1996/

A2.4 References

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Appendix A3

RVS-specific issues

A3.1 Introduction

SKB has developed a special tool, called RVS (Rock Visualisation System), for the modelling and visualisation of geological structures. RVS is an application which uses the CAD system /MicroStation®, 2002/ as its core. MicroStation has an extensive set of functions for creating and modifying geometrical objects in 3D, and in addition it can handle coupled information between the object and a database, analogous to a 3D GIS system.

The available capabilities of RVS are more extensive than it might appear in this appendix, and further development of the software is proceeding, to make it completely adapted to the methodology. The RVS system is described in detail in /Markström et al, 2001/. Below, we summarise the existing and planned functionality which make it possible to carry out modelling in RVS according to the methodology described in this report. If the functionality is only in the planning stage at the present time, this will be specially indicated. Here, we also demonstrate the implementation of QA (quality assurance) and TA (technical auditing) aspects.

A3.2 Coupling to databases (SICADA/SDE)

RVS is intimately coupled to SICADA and is capable of receiving and processing large quantities of data. The fundament of the RVS system is its capacity for fetching geographically related data from SICADA and quickly visualising them according to the needs of the user. The strength of RVS is the freedom to process primary data in order to highlight anomalies, and combinations of anomalies, in large amounts of data. Figure A3-1 shows schematically how data from site investigations stored in SICADA are used in RVS.

In order to create a platform for the construction and interpretation of a model in RVS, the primary data can be visualised in a variety of different ways. In RVS there are a large number of ways in which surface, borehole and tunnel data can be presented (Table A3-1). Each visualisation is traceable and can be reconstructed at a later time, and the possibilities of changing a visualisation after it has been carried out are limited, for the sake of traceability.

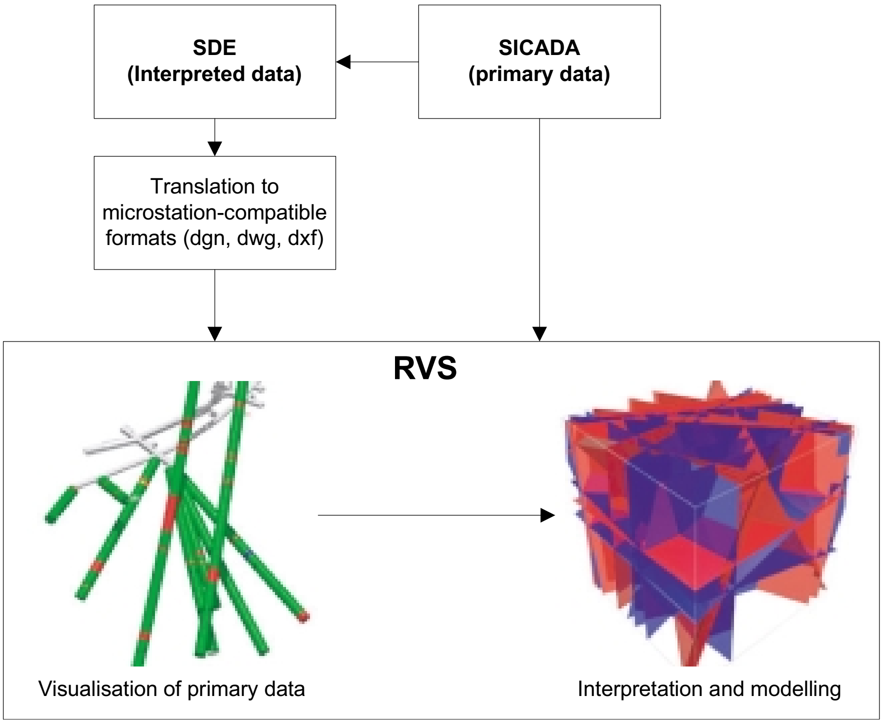


Figure A3-1. Flow diagram showing the way in which data are retrieved from SICADA and used in RVS for visualisation of primary data and subsequently for modelling.

Table A3-1. Visualisation of primary data from SICADA in RVS.

Type of primary data	Visualisation method	Comments
Surface data	Lines, surfaces	Lineament data are visualised as lines. Surface elements are derived from maps and are not stored in SICADA. Map data are taken into RVS by importing ASCII or DGN. It is planned to develop a function to import data directly from SDE
Borehole data	Cylinders, planes or curves	All data are coupled to a length coordinate which follows the borehole's extent
Tunnel data (investigation data from tunnel surveys)	Lines, surfaces	Tunnel data are usually taken in via ASCII or DGN

The user chooses the parameters which are to be downloaded from SICADA and then selects the visualisation form. RVS extracts data from the database and draws the diagram automatically (Figure A3-2).

All the visualisations of primary data and all imports of other graphic files are stored together with the model when defined in RVS. The model volume, name, position coordinates, etc are given by the user. The model is locked for unauthorised usage and can only be edited by the administrator or the designated user.

In order to create nestled models and to exploit earlier work, other RVS models can be shown parallel with the active project as background information. For instance, it is possible to work simultaneously with models in several different scales. Figure A3-2 shows the RVS working environment.

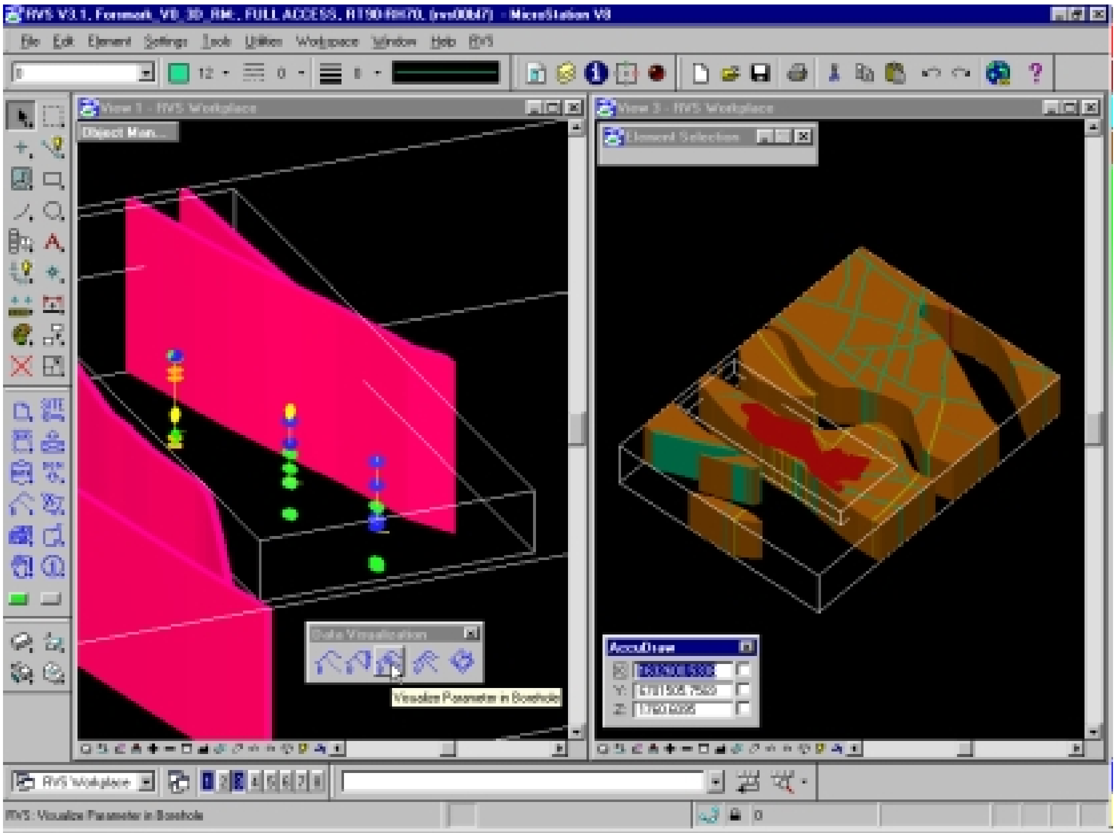


__Figure A3-2.__ The RVS working environment. In the left-hand window (view 1), radar reflections are visualised along 3 boreholes (primary data) and some modelled deformation zones. In the right-hand window (view 3), the block diagram produced in RVS shows a group of 3D objects (e.g. domains with particular properties).

Though a strong link between RVS with SICADA exists by design, a similar coupling to the GIS databases, SDE, is not yet implemented. However, it is possible to share data between theses quite different systems through common data formats such as Autocad drawings (dxf) or Microstation design files (dgn). Although not entirely satisfactory from a QA point of view, various conversion tools can be used to transform native GIS data such that it can be imported into RVS with no geometrical distortion.

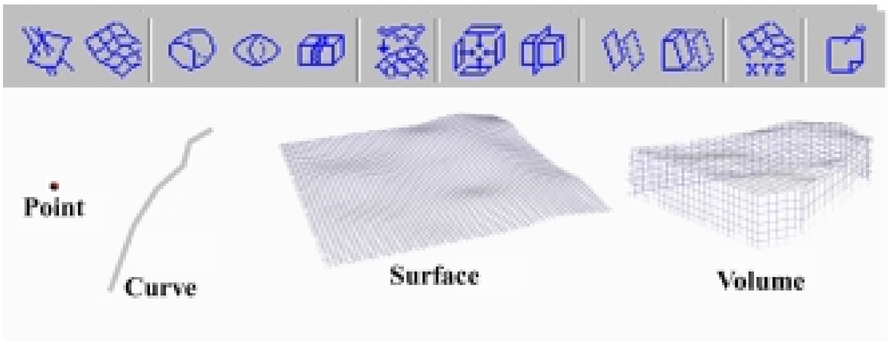
A3.3 Modelling of geometrical objects in RVS

In RVS, one has the possibility of creating four types of geometrical object, based on the visualised investigation data (primary data): points, curves, surfaces and volumes. A site descriptive model should as far as possible be described at each and every point. To attain this, a model volume is set up within which all the objects to be modelled can be contained. However, it is possible for primary data to lie outside this volume and still be used in the interpretation. The size of the model volume is determined in co-operation with all the persons who are likely to be users of the result. Models contain different degrees of detail, depending on scale, and a series of models with different scales can be created within the same coordinate system. However, the methodology of creating geometrical objects is the same at whatever scale.

Geometrical objects can be created with the aid of several different tools in RVS. Common to all these tools is that the geometry of the objects are not only saved as graphics but also in a local model database. It is possible to change the position, shape and extent of an object, and each change is registered in the local object database.

Figure A3-3 shows the different modelling alternatives which are used to create the four basic geometries. All types of geometry can be produced with the aid of coordinates, either in RVS or as imported ASCII data. The user can also position each object with the help of the cursor. Curves, surfaces and volumes can be bounded by other surfaces and volumes, which facilitate the modelling methodology. The modelling menu along the top of Figure A3-3 shows a number of existing tools for creating different geometries in a simple way.

In every model, there are two work settings, a modelling, "*thread*" setting in which the bounding surfaces, so called "*modelled structural surfaces*", of a volume are produced, and a "*solid*" setting, in which the solids, "*modelled structural volumes*", which are surrounded by the bounding surface are produced (Figure A3-4). Object types for points, curves and surfaces must be assigned in thread models, while object types for volumes must be assigned in block models.



Type of geometry	Coordinates	Graphic selection	Bounding surfaces	Bounding volumes
Point	•	•		
Curve	•	•	•	•
Surface	•	•	•	•
Volume	•	•	•	•

Figure A3-3. *Geometrical modelling alternatives in RVS. Each type of geometry can be defined with the help of up to four alternatives.*

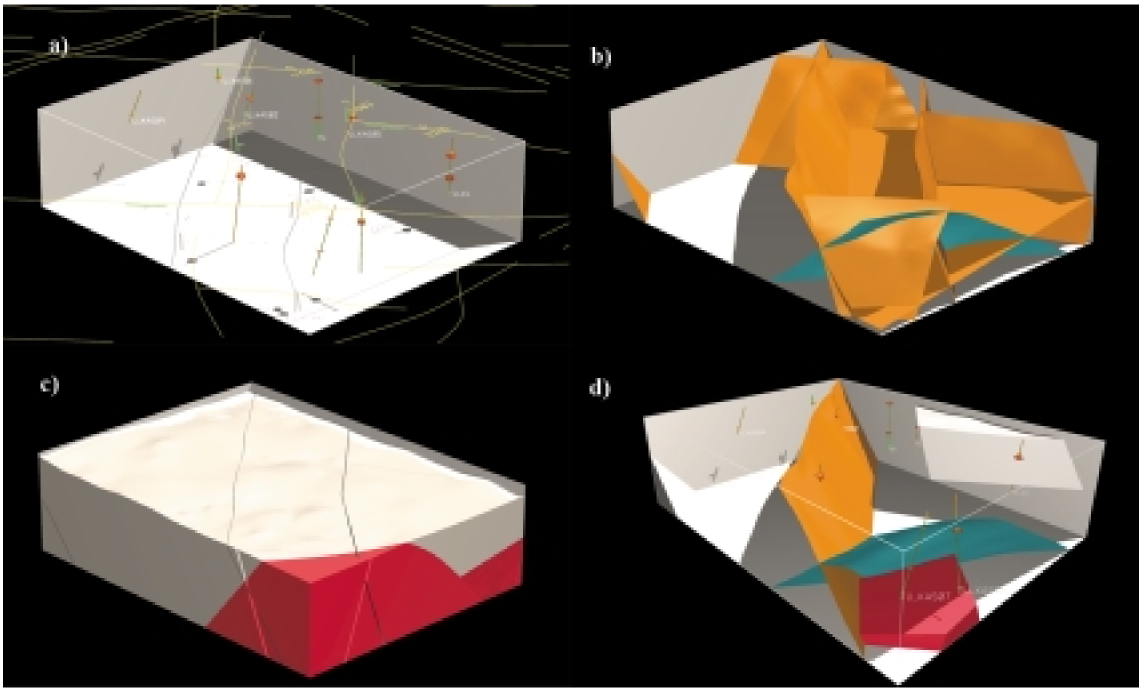


Figure A3-4. Examples of how different types of information and modelling objects can be visualised. (a) Visualisation of primary data from SICADA. (b) Modelled structural surfaces, which can be purely surface objects, such as fractures, or the bounding surfaces between volumes, such as rock boundaries. (c) Block model which has been automatically generated from the bounding surfaces in (b). (d) Different representations shown simultaneously, to facilitate modelling for the user.

A3.4 Assigning properties and object types in RVS

When a geometrical object has been created, the user must designate an object type via a type catalogue in RVS (see Figure A3-5). When the selection has been made, the user fills in the properties which the object represents via parameter tables, in accordance with the user's authorisations and with regard to available information. Figure A3-6 shows the menu of properties, which is presented to the user for the object type "rock unit". For each geometrical object, an object type is selected which in turn gives a selection of properties, which are valid for that object. Properties which are assigned to a particular object must be representative for the whole object. If an important parameter varies significant within an object, the object must be subdivided into smaller sub-objects. This means that properties with large variations in space are less suitable for modelling, since this leads to the creation of an unmanageably large number of objects. However, this can be handled to a certain degree by expressing the variability explicitly in the form of a statistical distribution function.

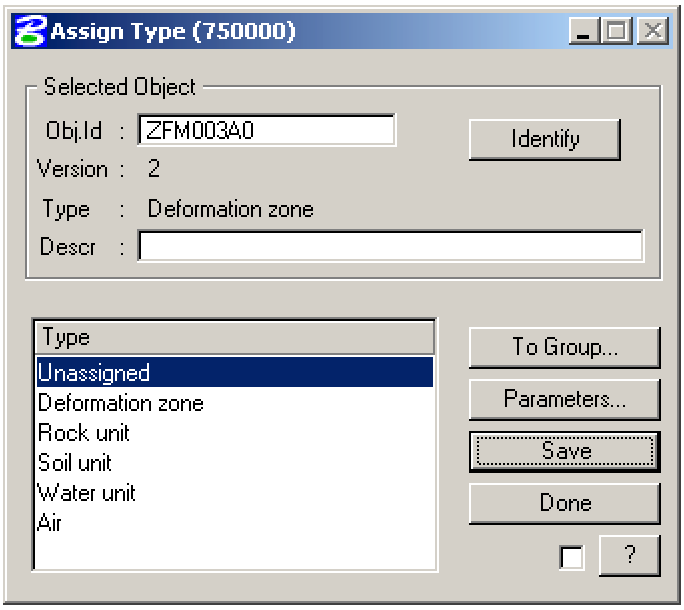


Figure A3-5. Main dialogue window in RVS for the assignment of object type.

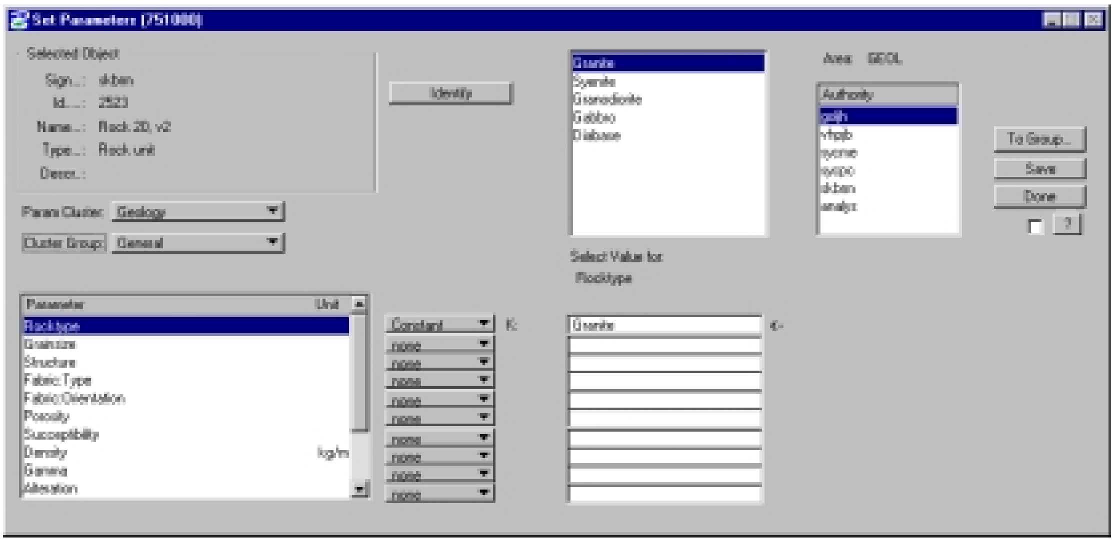


Figure A3-6. Dialogue window for the assignment of properties to objects in RVS, in this example for the object type "rock unit". The dialogue contains sub-dialogues in order to be able to describe, in this case, rocks in detail, as well as dialogues for stochastically defining fracture patterns.

A3.5 Model revisions

A3.5.1 General

The local RVS database is locked so that the user cannot alter its contents, once the ordered data from SICADA has been stored in the system. A control system ensures that the local database is a perfect copy of the actual data in SICADA. Every time a new data order is made, the existing local database is controlled and updated according to any changes or new information in SICADA. The user is given the possibility of updating existing visualisations, if the data in question have been changed.

A function, which is in the planning stage, will allow a user to subscribe to data which are especially important, such that the local database is automatically checked against SICADA at regular intervals, as arranged by the user. Updated, changed or new data of the type specified in the subscription, for example, borehole data, will be signalled to the user, who can then interactively update or complement the local database.

In order to make the handling of the models more secure, all objects are assigned a unique ID and labelled with the user's and the subject area's signature. The right to modify an object is reserved for the originator of the object, and the right to modify a parameter is reserved for members of the relevant subject area. These rights are administered centrally and updated at the start of each RVS session.

The construction of site descriptive models is a process which encompasses a number of geoscientific disciplines and which involves a large number of people. The process is carried out as stepwise development from an initial model which is often quite primitive. All models are part of a model chain in which each link is more or less dependent on the one before. So that mistakes do not become transmitted to other users, it is critically important that the model revisions are carried out in systematic manner, and that stable information channels are established to the different users.

The geometrical part of the models will be shared by many workers, which increases the likelihood that mistakes will be discovered. However, there is a real risk that the responsibility for the parameters will be unclear when the number of users is large; a model can be geometrically correct and still be defective in content. Most object types are described by a large number of parameters, of which a few may be incorrect. This type of mistake is often extremely difficult to uncover.

A strict treatment of model versions does not run counter to the possibility of creating alternative models, i.e. models in which the geometry or the properties diverge significantly from the base model. The term "model revision" is used for the quality-assured updating of a particular model. In general, model alternatives can co-exist in the model database, whereas only the latest revision of a particular model is accessible as a numbered model version. The administrator of the model database has nevertheless the possibility of linking different revisions, for tracing errors, etc.

In the following sections, we propose a manner of working which combines the iterative interpretation process with traditional document handling methods.

A3.5.2 Model database

In order to be able to control and retain an overview of all the steps in the modelling work, a central model database, SIMONE, will be established which will be administered by SKB. The model database will include only the geometrical models and their geoscientific properties, i.e. their object types and parameters. The model database will include all models, geometries and parameters which have been made public (made accessible to authorised persons), as well as details of all revisions, and will form the core of the quality assurance system which controls the modelling. Only the latest revision will be made accessible for modification and reprocessing by authorised persons using other numerical tools. Earlier modifications need to be locked and saved, to facilitate possible later searches for errors.

It is also intended to create an evolution history for each object and each model, using processing based on a document manager. This is possible because all objects will be given a unique identification number. The evolution history will contain the time of creation or modification of all objects, object types and parameters, as well as user information and version number.

The model database should be mainly used for structuring the collection of model versions and for handling the current model. By means of keeping strict control over the model versions, external groups which use the geoscientific models, for example, hydrogeology or rock mechanics groups, can retain traceability back in time and also suggest changes or additions to the current model. The model database should therefore be able to accept new or modified geometrical objects which have been interpreted outside the primary geoscientific modelling tool (RVS).

Figure A3-7 shows schematically the planned structure for managing model versions, which is intended to be the same for all model alternatives. Revision numbers designate model alternatives and the phase of investigation the model represents, as well as the current revision number for minor revisions.

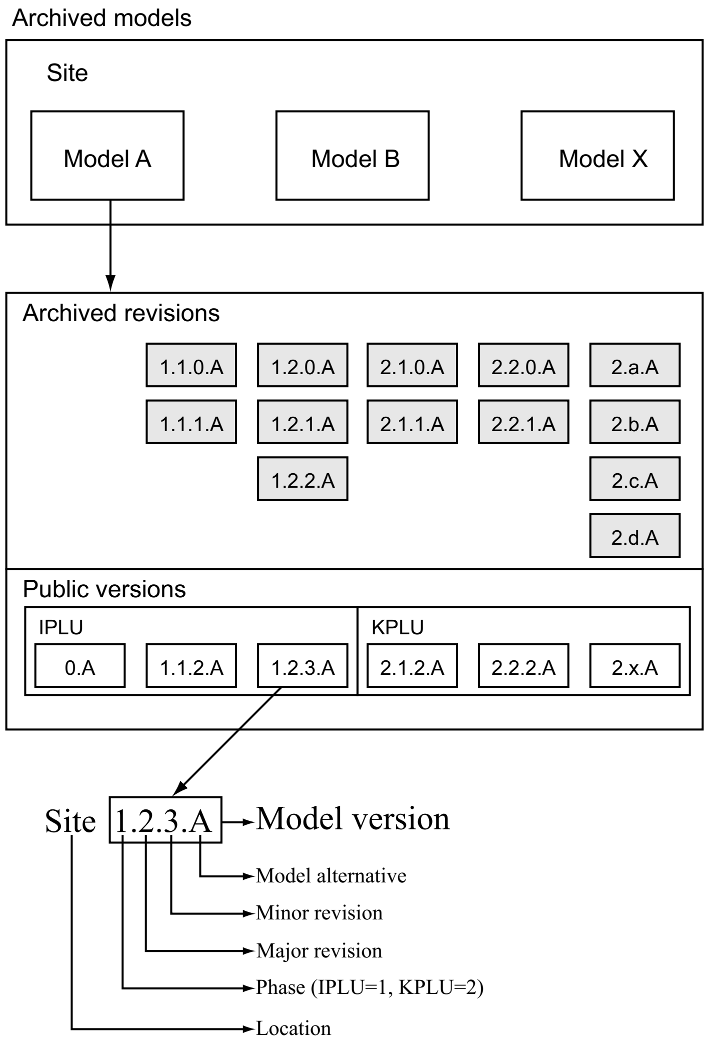


Figure A3-7. *Schematic structure for managing model revisions in the model database. For each alternative model (alternative interpretation) A, B, etc, there exist a number of revisions. The process is identical for all model alternatives. The revision number indicates which phase of investigation the model represents, such that 1 corresponds to the phase of investigation, A corresponds to the model alternative, and the decimals indicate the version number. The nomenclaturial system is shown on the example of version number ILPU 1.2.3.A (IPLU = initial site investigation phase, KPLU = complete site investigation phase).*

It is planned to treat single objects within a model in a corresponding manner. Every object which is created should have a thread of events which is continuously traceable. With the help of this, all the geometrical variants in an objects history should be traceable, as well as changes in object type and parameters. This type of book-keeping should make it possible for the person responsible for model management to, step by step and object for object, follow a model's development. At present, this functionality can only be made accessible to the system administrator, to be used when looking for errors, etc. If the necessity exists, also users of the system might be able to take advantage of this functionality as an exploration tool for model construction. A schematic illustration of the system for object revision is shown in Figure A3-8.

Revisions of a model take place as a continuous process which consists of many steps. The number of revisions of most objects is expected to be quite large. However, it is extremely important to limit the number of model revisions to a minimum, in order to reduce the amount of data and to retain an overview of the model database. In this context, it is important to distinguish *major revisions*, which can affect a large number of users, from *minor revisions*, which only affect one particular user, and it is also important to distinguish between *revisions of geometry* and *revisions of object types* and parameters. All revisions of geometry, whether major or minor, will be made in consultation with the whole user group (e.g. at the regular site meetings). With regard to object type and parameter revisions, it is suggested that only major revisions need whole group consultation, i.e. should only be published after achieving consensus amongst the persons responsible for the different subject areas. Minor revisions of object type or parameter may published by the responsible subject area leader, without necessarily consulting with the other subject areas, although the obligation to inform about such revisions at the regular site meetings remains.

In practice, major revisions are such that they have a significant effect on geometrical relationships, for example, the addition or deletion of a deformation zone, whereas minor revisions are more adjustments to an objects type or its parameters. Also the latter, however, can be critical for some of the other users under certain circumstances. The judgement as to whether a revision should be considered as "major" or "minor" is, and must be, subjective, and cannot be regulated, hence the obligation to consult and inform at the site meetings must be strictly followed.

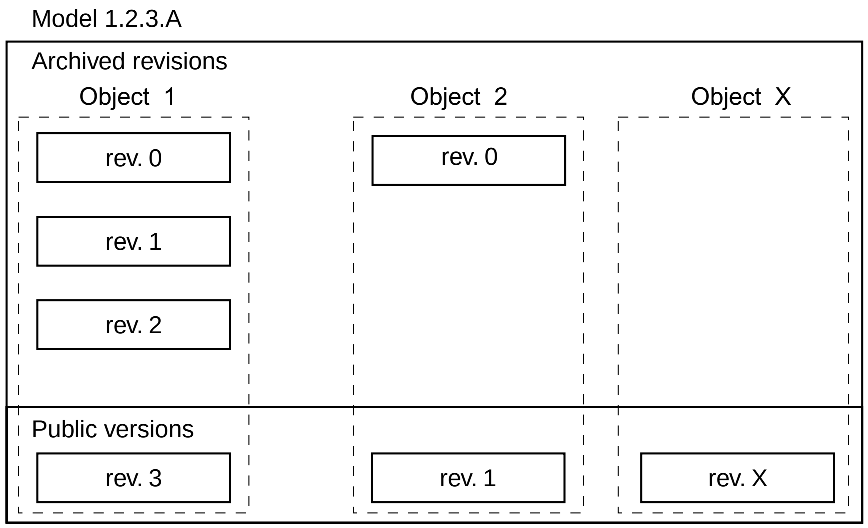


Figure A3-8. *Schematic diagram to illustrate the system planned to manage object revisions. All modifications of an objects geometry and type are accounted for in a system which is controlled by the system administrator.*

A3.5.3 Revision description

We recommend that users of the geoscientific models, with certain exceptions, should only have access to the latest model version. When a major model revision is published, all authorised users of the model should be informed with the aid of model revision description. This is a document in which all previous major model revisions are described, together with the corresponding references. The persons responsible for the model decide when there is sufficient reason for publishing a revised model. This decision is based on a judgement of whether the revision has significant effect on the use of the geoscientific model.

A3.5.4 Parameter control

It should not be necessary to make a new model description when minor revisions have been published. The user must himself/herself judge how much the revision affects his/her work. Because of the great variety of parameters, this implies that minor changes are difficult to detect and trace. A special tool is planned which will allow the user to subscribe to revisions of single objects, single object types or single parameters. Using such a procedure, it can be ensured that information which is critical for the user is received. That the user must actively either include or reject the subscribed change means that he/she has made a decision as to its relevance for his/her project, and hence taken responsibility for possible consequences.

A strict management of model and object revisions ensures that the most recent version of a certain model is always used for the different types of simulations and analyses. That all users have access to the same model and object database improves the possibility of identifying incompatible model and object versions, and errors in an object's geometry. Since the geometries in a model are interrelated, and are intimately associated geoscientifically, the risk that an erroneous object can exist over a long period of time is, in practice, quite small. On the other hand, errors in the parameters assigned to a certain object can be long-lived, and can have serious consequences for subsequent analyses. Hence, it is necessary to create a system to control the parameters assigned to objects.

An object's type is defined in such a way that it has general validity and is applicable in all geoscientific subject areas. However, each object type is assigned a number of parameters which can have different importance for different subject areas. For example, the parameter "hydraulic conductivity" in a rock unit will have less significance for the subject area rock mechanics than for the subject area hydrogeology, whereas the opposite will be the case for, for example, the parameter "Poisson's number". In contrast, the parameter "fracture intensity" will be of great significance for both those subject areas. Hence, for each parameter, there will be a need to regulate which instance has responsibility for the assignment of a certain parameter and that it is correctly calculated.

Every parameter is made available for modification solely to authorised persons, under normal circumstances, the person responsible for the relevant discipline. This gives the other users the security that the parameters in question have been sanctioned by the responsible person, and that they can be used for calculations until further notice. It also makes it possible for the users to trace the source of the parameters, in case a problem should arise in subsequent processing, or in case an error is discovered. As in the case of models and their different objects, all parameter revisions should be saved, to facilitate trouble shooting and to secure traceability in the different phases of the modelling.

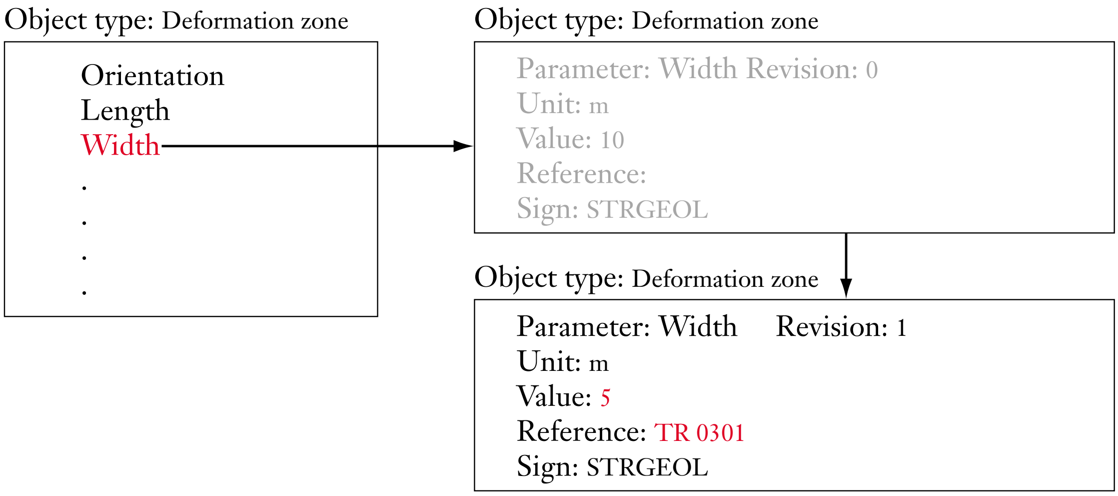


Figure A3-9. *Hypothetical example of how the revision of a parameter is managed (for explanation, see text).*

Figure A3-9 shows a hypothetical example of the principles of modifying a parameter in a model. The parameter "width" has been modified with respect to "value" and "reference". The parameter lies within the responsibility of the discipline "Geology" , sub-discipline structural geology, here shortened to STRGEOL. This discipline and sub-disipline has the sole responsibility for this particular parameter. The process by which the parameter was calculated should be detailed under "reference", in this case, a report. Only the most recent revision, here revision 1, is accessible in the model database, but earlier revisions can be accessed by the system manager, for example, when looking for the source of an error.

A3.5.5 New objects in the model database

The construction of models is an iterative process which requires interaction between different scientific disciplines. The present methodology involves in practice that an empty geometrical framework is created, in which different types of object are successively added and modified. Most of the geometrical objects in the models, however, will be the responsibility of the discipline "geology", i.e. the position, extent, orientation, etc, of fracture zones, and the distribution of the different rock types. In contrast, most of the properties of the objects (parameters) will probably be the responsibility of other subject area groups, which means that data, based on calculations or expert judgements, will be assigned to the current objects according to the guidelines outlined in the previous section.

However, there may sometimes be a need for a discipline group other than "geology" to introduce new geometrical objects into the common model database. Since the responsibility for different types of object and object types is regulated, such additions will anyway be subject to a system of controls. For instance, it should not be possible for the "rock mechanics" group to introduce a new geological object, e.g. a fracture zone, without conferring with the discipline group "geology", which is responsible for modifications of such object types. In the same way, the hydrogeological parameters of such a fracture zone are the responsibility of the discipline "hydrogeology", whose acceptance is required for any modification. The control system forces a consensus to be reached with regard to the common, geological objects. This may seem to be a cumbersome process, but in practice it simply requires a very close cooperation between the different discipline groups. If it should happen that a consensus cannot be reached, for example, because of a lack of, or contradictory, information, the situation can be managed best with alternative models.

Apart from the common geological objects, there are a number of object types which are only used in special situations or become common features of the model only in its later stages of construction (e.g. iso-surfaces, tunnels, equipment, etc). The introduction of new object types follows the same principles as the modification of object types (see above). If the changes are judged to be significant, they are treated as a major model revision, if not as a minor revision.

Finally, there are a two "generic" objects which can be incorporated to ensure flexibility in the modelling and to offer some freedom of action in case the pre-determined object types are unsuitable in a certain situation or description. These object types, called "miscellaneous surface" and "miscellaneous volume", are the responsibility of the discipline group which creates the object, and modifications of such objects should follow the same principles as for the other objects, i.e. modification is reserved for the originator, and publication can only occur after conferring with the other groups.

A3.6 References

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