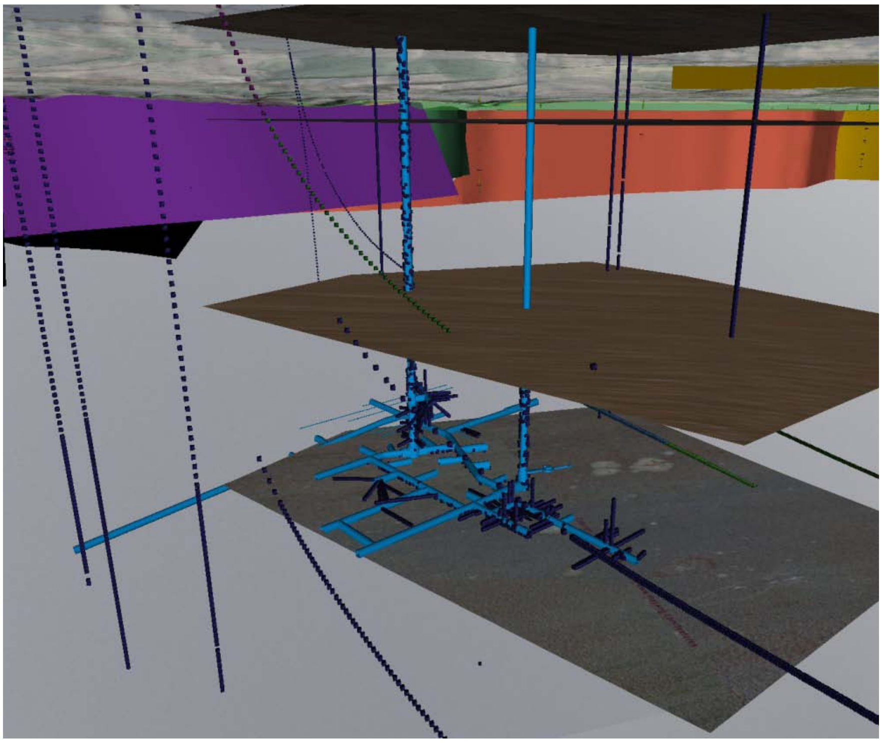
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

# Interpretation and Modelling: Geology, to support the development of an Integrated Site Descriptive Model

MINERALS and WASTE Programme

Open Report OR/11/057



BRITISH GEOLOGICAL SURVEY

MINERALS and WASTE PROGRAMME

OPEN REPORT OR/11/057

# Interpretation and Modelling: Geology, to support the development of an Integrated Site Descriptive Model

Shaw, RP; Everett, P; Beamish, D; Chadwick, RA; Kingdon, A; Marchant, AP; Napier, BJ; Pharaoh, TC; Powell, JH; West, JM; and Williams G

*Front cover*

Screen shot of the GeoVisionary visualisation of the Andra Bure URL

*Bibliographical reference*

SHAW, RP; EVERETT, P; BEAMISH, D; CHADWICK, RA; KINGDON, A; MARCHANT, AP; NAPIER, BJ; PHARAOH, TC; POWELL, JH; WEST, JM; AND WILLIAMS G. 2011. Interpretation and Modelling: Geology, to support the development of an Integrated Site Descriptive Model. *British Geological Survey Open Report*, OR/11/057. 154pp.

Keyworth, Nottingham British Geological Survey 2011

This report has been prepared by the British Geological Survey under contract to NDA. The report has been reviewed by NDA, but the views expressed and conclusions drawn are those of the authors and do not necessarily represent those of NDA.

**Conditions of Publication**



**Bibliography**

If you would like to see other reports available from the NDA, a complete listing can be viewed at our website www.nda.gov.uk, or please write to the Communications Department at the address below.

**Feedback**

Readers are invited to provide feedback to the NDA on the contents, clarity and presentation of this report and on the means of improving the range of the NDA reports published. Feedback should be addressed to:

Dr Elizabeth Atherton
Head of Stakeholder Engagement and Communications
Nuclear Decommissioning Authority
Radioactive Waste Management Directorate
Building 587
Curie Avenue
Harwell Oxford
Didcot
Oxfordshire OX11 0RH

e-mail rwmdfeedback@nda.gov.uk

## Acknowledgements

This report has drawn on a large number of published sources, both in peer reviewed journals and from the extensive bibliographies of the radioactive waste management organisations whose investigations are summarised here and whose web sites are often comprehensive sources of information on the work that they are doing. For most of the national programmes covered in this report unpublished sources and discussions with members of staff have helped to fill in some of the details. They are all thanked for their willingly given information and insight.

# Contents


CONTENTS III

EXECUTIVE SUMMARY 1

1 INTRODUCTION 5

1.1 Background 5

1.2 Overall work package Objectives 6

1.3 Approach 7

1.4 Objectives for Geological Interpretation and Modelling 8

1.5 Report Structure 9

2 CONTEXT OF INTERNATIONAL PROGRAMMES 12

2.1 United Kingdom 12

2.2 France 13

2.3 Sweden 13

2.4 Finland 15

2.5 USA – WIPP 16

2.6 Germany – Gorleben 16

2.7 Switzerland 18

2.8 Summary 19

3 APPROACHES TO INTERPRETATION AND MODELLING 21

3.1 The Nirex Sellafield example 21
3.1.1 Introduction 21
3.1.2 Mapping (topographical, geomorphological and geological) 22
3.1.2.1 Topography 24
3.1.2.2 Geological Mapping 24
3.1.2.3 Geomorphological Mapping 25
3.1.3 'Basement' rocks - nature, distribution and properties 26
3.1.3.1 Borehole integration exercise 27
3.1.3.2 Onshore/Offshore Integration 29
3.1.3.3 Surface base fracture mapping 29
3.1.4 Sedimentary rocks - nature, distribution and properties 29
3.1.5 Superficial (drift) deposits - nature, distribution and properties 30
3.1.6 Geological structure 31
3.1.7 Mineral Deposits 34
3.1.7.1 Mineral exploration boreholes 34
3.1.7.2 Iron mine plan study 35
3.1.7.3 Main Band Colliery fracture mapping 35

3.1.8 Spatial heterogeneity 35
3.1.9 Interpretation of structural domains from discontinuity data 38
3.1.10 Potentially Flowing Feature Logging 42
3.1.11 Tectonics 43
3.1.11.1 Seismic Hazard 43
3.1.11.2 In-Situ Stress 43
3.1.12 RCF Predictions 44
3.1.13 Summary of approaches used and their application 46

**3.2 The SKB Forsmark and Laxemar Examples 48**
3.2.1 Mapping (topographical, geomorphological and geological) 50
3.2.2 Basement rocks - nature, distribution and properties 51
3.2.3 Superficial (drift) deposits - nature, distribution and properties 51
3.2.4 Geological structure 52
3.2.5 Geological Interpretation and Modelling 53
3.2.6 Modelling 54
3.2.7 Model volumes and model areas 55
3.2.7.1 Regional model area and volume 56
3.2.7.2 Local model area and volume 56
3.2.8 Mineral deposits 57
3.2.9 Spatial heterogeneity 57
3.2.10 Visualization 57
3.2.11 Tools for logging 58
3.2.11.1 Boremap 58
3.2.11.2 BIPS - Borehole Image Processing System 58
3.2.12 Summary of approaches used and their application 58

**3.3 The posiva Olkiluoto Example 70**
3.3.1 Basement rocks - nature, distribution and properties 70
3.3.2 Superficial (drift) deposits - nature, distribution and properties 71
3.3.3 Geological structure 71
3.3.4 Mineral deposits 72
3.3.5 Summary of approaches used and their application 72

**3.4 The Andra Bure Example 78**
3.4.1 Introduction 78
3.4.2 Mapping (topographical, geomorphological and geological) 78
3.4.2.1 Topography 78
3.4.2.2 Geological Mapping 78
3.4.2.3 Geomorphological Mapping 78
3.4.3 Sedimentary rocks - nature, distribution and properties 79
3.4.4 Superficial (drift) deposits - nature, distribution and properties 80
3.4.5 Geological structure 80
3.4.6 Mineral deposits 81
3.4.7 Spatial heterogeneity 81
3.4.8 Visualisation 81
3.4.9 Summary of approaches used and their application 82

**3.5 The Nagra Opalinus Clay Example 89**
3.5.1 Introduction 89
3.5.2 Mapping (topographical, geomorphological and geological) 89
3.5.3 Sedimentary rocks - nature, distribution and properties 90
3.5.4 Spatial heterogeneity 91
3.5.5 Geological Evolution 91
3.5.6 Summary of approaches used and their application 92

**3.6 The BGR Gorleben Example 96**
3.6.1 Mapping (topographical, geomorphological and geological) 96
3.6.2 Sedimentary rocks - nature, distribution and properties 97
3.6.3 Superficial (drift) deposits - nature, distribution and properties 98

3.6.4 Geological structure 98
3.6.5 Mineral deposits 99
3.6.6 Spatial heterogeneity 99
3.6.7 Geological Evolution 99
3.6.8 Summary of approaches used and their application 100

**3.7 The DoE WIPP Example 104**
3.7.1 Mapping (topographical, geomorphological and geological) 104
3.7.2 Sedimentary rocks - nature, distribution and properties 104
3.7.3 Superficial (drift) deposits - nature, distribution and properties 105
3.7.4 Geological structure 105
3.7.5 Mineral deposits 105
3.7.6 Tectonics 105
3.7.7 Summary of approaches used and their application 106

**3.8 Summary 109**

**4 OTHER SECTORS 113**

**4.1 CCS and gas storage 113**
4.1.1 Storage site characterisation 113
4.1.1.1 Geological characterisation 113
4.1.1.2 Reservoir structure 114
4.1.1.3 Reservoir properties 114
4.1.1.4 Caprock properties 114
4.1.1.5 Overburden properties 114
4.1.1.6 Fault properties 114
4.1.2 Predictive flow modelling 115
4.1.3 Site monitoring 115
4.1.4 Assessment of the rock mass 115
4.1.4.1 Enhanced seismic imaging 115
4.1.4.2 Sub-seismic scale fracture characterisation 115
4.1.4.3 Geomechanical characterisation 116
4.1.4.4 Multi- (and wide-) azimuth seismic acquisition 116
4.1.4.5 Lithological discrimination seismic inversion 116

**4.2 Hydrocarbon Exploration/Exploitation including shale gas 116**

**4.3 Mining Industry 117**
4.3.1 Coal Mining 117
4.3.2 Bedded ore and related deposits 117
4.3.3 Non-bedded ore and related deposits 117

**4.4 Applications of Three-Dimensional Geological Modelling in Geological Survey Organisations 118**
4.4.1 Datasets required for 3D Geological Modelling 118
4.4.1.1 Digital Terrain Models 118
4.4.1.2 Borehole Drilling Logs 119
4.4.1.3 Lithologic Dictionaries and Stratigraphic Lexicons 119
4.4.1.4 Colour Ramps 119
4.4.1.5 Optional Data Sets 119
4.4.2 Common 3D Mapping and Modelling Software 120
4.4.3 Some of the lead players in GSO 3D Modelling 121
4.4.4 Geological Data Integration and Interoperability 122
4.4.5 High resolution airborne surveys 123
4.4.6 Integrated Interpretation and Digital Field Mapping 124

**4.5 Summary 125**

**5 RESOURCES 127**

**5.1 3D modelling hardware and software 127**

**5.2 GIS Software 128**

**5.3 Geophysical data prossessing hardware and software 129**

**5.4 Expertise 130**

**5.5 Summary 130**

**6 GEOLOGICAL MODELLING – TOOLS FOR INTERPRETATION AND MODELLING 131**

**6.1 Summary of Geological Modelling and interpretation Methods and Tools 131**
6.1.1 Mapping (topographical, geomorphological and geological) 131
6.1.2 Geological structure, nature, distribution and properties of rocks 132
6.1.3 Spatial heterogeneity 132
6.1.4 Interpretation of structural domains from discontinuity data 133
6.1.5 Potentially Flowing Feature Logging 133
6.1.6 Tectonics 133
6.1.7 Geophysical survey interpretation (seismic, non-seismic and wireline) 133
6.1.8 Mining 133
6.1.9 Seismic survey interpretation 134

**6.2 Developments in other sectors relevant to a new UK programme 134**

**6.3 Implications for specific host rocks 135**

**6.4 Interpretation and Modelling of Data Arising from a UK Site Investigation Programme 135**

**6.5 Summary 136**

**7 CONCLUSIONS 138**

**7.1 Main conclusions 138**

**8 REFERENCES 140**

## FIGURES

Figure 1 The Nirex study areas around Sellafield in West Cumbria (from NIREX, 1997a)...... 23

Figure 2 Generalised structural setting of the Sellafield Study Area (from NIREX, 1997a). ... 25

Figure 3 Block model of the PRZ map area produced using earthVision. The Permo-Triassic sediments have been removed from one quadrant of the model to expose the internal geometry of the basement rocks (from NIREX, 1997a). ........ 33

Figure 4 Rock mass characterisation at Sellafield. Permeability derived from acoustic impedances computed by inversion of 3-D seismic dataset. ........ 38

Figure 5 Part of the Structural Atlas summary for RCF3. Note that the upper half of the image is Permo-Triassic and the lower part BVG. Even at the scale of reproduction above differences in fracture density (purple histograms) and orientation (rose diagrams) within the BVG are distinguishable (Nirex 1996). ........ 41

Figure 6 Example HiRES data from the Anglesey survey, EM: Apparent resistivity, 0.912 kHz (from White and Beamish 2010). ........ 124

## TABLES

Table 1 Data used in the compilation of the Structural Atlas (Nirex 1996). 39

Table 2 Fracture mineralisation chronology, principal associated minerals and mineralisation types in Sellafield boreholes. 42

Table 3 Inventory of methods used by Nirex in their Sellafield investigations 1988-1997 and main purposes that the data were used for. 48

Table 4 Forsmark site investigations with data freeze dates (SDM – Site Description Model) 49

Table 5 Laxemar-Simpevarp site investigations with data freeze dates 49

Table 6 Inventory of all available geological, geophysical, borehole and geotechnical data with an explanation of their useage and handling in the SDM-Site Forsmark modelling (data extracted from SKB (2007)). 61

Table 7 Inventory of all available geophysical, geological, thermal, mechanical, geotechnical, hydrogeological, and hydrogeochemical data as well as in-situ and laboratory based material testing methods, with an explanation of their useage and handling in the SDM-Site Laxemar modelling (data extracted from SKB (2009), source references also given in this report). 69

Table 8 Summary of investigations undertaken by Posiva with an explanation of their use for characterisation of the Olkiluoto site, including studies undertaken at the ONKALO rock characterisation facility at Olkiluoto. Summarised and taken from Posiva Report 2009-01. *Assessment Report: General Summary.* 77

Table 9 Summary of data collected from hydrogeological, geophysical, and geological investigation techniques with an explanation of their use for characterisation of the Bure site, including a summary of relevant experiments, monitoring and testing activities at the Meurse/Haute-Marne underground laboratory which are useful for modelling purposes. Summarised from Andra 2005a; *Dossier Argile – Synthesis* 88

Table 10 Summary of data collected from hydrogeological, hydrochemical, geophysical, and geological investigation techniques as well as testing in underground rock laboratories and other research facilities employed by Nagra in order to achieve a siting proposal and a site descriptive model for a potential repository site. 95

Table 11 Summary of data collected from in-situ and lab-based geomechanical testing methods, as well as hydrogeological, geophysical, geothermal, and geological exploration activities with an explanation of their use for characterisation of the Gorleben site. Summarised from Bornemann et al., 2008 and Bräuer et al., 2011. 103

Table 12 Summary of data collected from hydrogeological, geophysical, and geological investigation techniques with an explanation of their use for characterisation of the WIPP site. Summarised from Borns (1997) and Kuhlman and Barnhart, (2011). 109

Table 13 Summary of key approaches used by the seven programmes reviewed in this report. 111

Table 14 Phases in the development of the geological understanding of a site during site characterisation activities. 136

# Executive Summary

Taking into account the experiences of sister organisations and best practice in other sectors such as oil and gas it is anticipated that the characterisation of the site will best be undertaken by the development and progressive updating of a single integrated Site Descriptive Model, i.e. a model describing the geometry, properties of the bedrock and water, and the associated interacting processes and mechanisms, which will be used to address the information requirements of all the end users (NDA 2010). Such an approach will ensure that

- The understanding of the different aspects of the geosphere such as the geology, hydrogeology and hydrochemistry is developed in a consistent manner; and
- The different end users base their design and assessments on the same understanding and evidence base.

There are several elements to the preparation of a Site Descriptive Model, including:

- Definition of the volume of ground that needs to be included in the model;
- Subdivision of the model into geometric units so as to permit the description of spatial variability in a meaningful manner; and
- Assignment of parameters (values and/or statistical distributions) to the defined geometric units.

It is anticipated that, in a similar way to the approach adopted by SKB and Posiva, the integrated Site Descriptive Model will be divided into parts comprising clearly defined disciplines which may form either chapters or discipline-based models. The discipline-based models that are likely to be developed for UK sites comprise the following:

- Geology;
- Hydrogeology;
- Hydrochemistry;
- Geotechnical;
- Transport properties;
- Thermal properties; and
- Biosphere.

The Site Descriptive Model will provide the understanding of the characteristics of the site, sufficient to allow further qualitative and quantitative modelling to be undertaken as part of the development of the Environmental Safety Case.

Some work has been undertaken by RWMD on the process of modelling and interpretation, the majority of the work to date has focussed on gaining an increased understanding of the various data acquisition techniques. This report provides a description of the state-of–the-art processes and techniques available for the modelling and interpretation of site characterisation

data in the geology discipline to support the development of facilities for the long term disposal of higher activity radioactive waste.

This report describes the various techniques which have been adopted by a number of radioactive waste management organisations and their contractors, with a particular focus on those whose site selection/characterisation programmes are at an advanced stage, to translate acquired data into understanding to support site descriptions, as part of their site characterisation programmes. It is focussed on their geological interpretation and modelling approaches though the data and models are important in other disciplines that are the subject of separate reports, in particular hydrogeology and engineering design. The programmes considered, noted below, have been chosen to provide sufficient detail such that the issues associated with the characterisation of the various geological environments typical of the UK are determined. The three potential host rocks being considered by RWMD are:

- Higher strength rocks - these would typically comprise crystalline igneous and metamorphic rocks or geologically older sedimentary rocks where any fluid movement is predominantly through discontinuities (e.g. fractures);
- Lower strength sedimentary rocks - these would typically comprise geologically younger sedimentary rocks where any fluid movement is predominantly through the rock matrix; and
- Evaporites - these would typically comprise anhydrite (anhydrous calcium sulphate), halite (rock salt) or other evaporites that result from the evaporation of water from water bodies containing dissolved salts.

This report draws from experience gained from the following site characterisation programmes.

- Andra, France (mudrock investigations near Bure);
- SKB, Sweden (crystalline rock without cover – Laxemar and Forsmark sites);
- Nirex, UK (crystalline rock with cover – Sellafield and Dounreay);
- WIPP, USA (bedded salt);
- Posiva (crystalline rock without cover – Olikiluoto);
- Nagra, Switzerland (both crystalline and mudrock investigations);
- DBE, Germany (salt dome – Gorleben);

The focus of this review is on the first four of these programmes with the others used to provide information from a different perspective, for example bedded salt versus diaperic salt. These programmes have been selected because they investigated rock types and geological environments that are representative of those that are most likely to host a repository in the UK. The geological setting investigated by each programme and the methods used to investigate and interpret the geology of each site are summarised.

During the course of the work undertaken for this review it became apparent that there are a number of observations that are relevant to the development of a site investigation programme by the NDA-RWMD. Despite the vintage of the Nirex investigations, particularly at Sellafield but also those at Dounreay, the range of techniques applied and their application is the most comprehensive of the programmes reviewed here. This is partly because the basement under sedimentary cover geological environment investigated at these two sites is the most geologically varied of the situations considered here but also because Nirex ensured that they were able to develop good geological understanding of the sites by applying a wide range of methods. In collaboration with their contractors, this included a significant amount of development in the application of methods to geological situations outside their then 'comfort zone' as well as testing new developments and novel techniques some of which have now become standard practice in this and other sectors. For example, the wireline logging suite adopted by Nirex and the development of some of the down-hole logging tools undertaken during the Sellafield investigations as well as their application to a non-sedimentary environment was far more comprehensive than that adopted by any of the other programmes reviewed here. Thus the summary descriptions provided in the sections below for the Nirex investigations are comprehensive and are less detailed for the other programmes because many of the methods applied are the same.

The account of the national programmes reviewed in this report illustrates that most techniques to obtain geological data and its subsequent interpretation are common to all the examples e.g. surface geophysics, seismic surveys, use of geological information from boreholes. The level of sophistication in interpreting the information so that it can be used in geological site models appears to be a function of the complexity of the geological setting and when the programme was operational.

Analysis of additional processes and tools that are used for site characterisation in other industries, primarily the carbon capture and storage sector which utilises approaches from the hydrocarbon industry, shows that for many sectors the interpretation and modelling of geological information is critical and is primarily focussed on the specific needs of that particular sector. Nevertheless, standard industry products and practices are available for the baseline geophysical analysis and interpretation. Other more specific software packages are needed for more sophisticated modelling of such data. These are largely based on those used in the hydrocarbon industry and it is this sector that historically has driven new developments in data acquisition, processing and interpretation methods and techniques. There are a range of commercial 3D digital geological modelling and GIS packages readily available capable of fully supporting the development of geological site descriptive models for all of the geological environments likely to be examined during a new site investigation programme in the UK.

In terms of resource availability, the software, hardware and expertise required for the interpretation and geological modelling aspects of a new site characterisation programme in the UK already exist and are widely commercially available. We do not believe that there will be a requirement for the bespoke development of software applications in respect of any of the geological environments likely to host a UK repository. Similarly there are no unusual hardware requirements and all necessary hardware is readily available off-the-shelf. While we expect that some training will be required for some of the geological environments and rock types that may be encountered in the new UK programme, we believe that there are skilled geoscientists capable of undertaking all of the interpretation and modelling activities that will be required. However, attracting appropriate skilled staff from other sectors may be difficult. If two sites with similar geologies are characterised in parallel it is possible that some specialist areas may be stretched unless appropriately scheduled.

With regard to the use of tools for geological modelling, broadly, all reviewed national radioactive waste programmes have utilised methods and software developed in other sectors, principally the hydrocarbon industry, for geological interpretation and modelling. There are also now new methods of interpretation which have not been used in the reviewed national programmes which, we believe, would enhance the geological understanding in a future UK site investigation programme if used. However, we believe that all the necessary software, hardware and methodologies necessary for a future programme are currently readily available.

# 1 Introduction

## 1.1 BACKGROUND

In order to adequately characterise an area to determine its suitability to host a deep geological disposal facility it is necessary to examine a relatively wide area, for example to determine the geological framework of the site and establish groundwater flow models as well as to characterise the actual volume of rock within which the disposal vaults are to be constructed (Nirex 2005). In order to define the geological framework for a particular site area and whether it is suitable for use in subsequent safety assessment studies, it is likely to be necessary to undertake geological investigations over a wide geographical area. Such investigations are likely to include geophysical surveys, geological mapping and the establishment of the near-surface hydrogeology and surface hydrology. The extent of this area within which features having direct relevance to the potential geological disposal facility occur will depend on the geological environment.

Interpretation of the data acquired from site investigation activities forms an integral part of the overall programme of site characterisation. The process of site characterisation comprises five inter-related stages (Nirex 2005):

- Data acquisition – to obtain measurements and to collect data utilising a range of measurement techniques and surveys;
- Data processing – to transform measurement data into information that is meaningful in terms of the properties of the site;
- Interpretation – to understand the significance of that information in terms of the individual aspects of the site (e.g. groundwater flow, geology, environmental processes, etc);
- Integration – to develop a self consistent understanding of the site as a whole and that includes all the individual aspects; and
- Communication – to communicate the understanding obtained to others (e.g. those involved in performance assessment, engineering design and key stakeholders) and to obtain feedback that could influence the ongoing process of site characterisation.

In its broadest sense, interpretation embraces data processing, interpretation and integration. These interpretation activities are undertaken iteratively with initial stages of interpretation being used to develop understanding and to identify data gaps or uncertainties that are used to inform further stages in the data acquisition and interpretation activities. Thus, as the process proceeds, the characterisation activities, both data acquisition and interpretation tend to become more targeted and focussed on significant features of the site.

Taking into account the experiences of sister organisations and best practice in other sectors such as oil and gas it is anticipated that the characterisation of the site will best be undertaken by the development and progressive updating of a single integrated Site Descriptive Model, i.e. a model describing the geometry, properties of the bedrock and water, and the associated interacting processes and mechanisms, which will be used to address the information requirements of all the end users (NDA 2010). Such an approach will ensure that:

- The understanding of the different aspects of the geosphere such as the geology, hydrogeology and hydrochemistry is developed in a consistent manner; and
- The different end users base their design and assessments on the same understanding and evidence base.

There are several elements to the preparation of a Site Descriptive Model, including:

- Definition of the volume of ground that needs to be included in the model;
- Subdivision of the model into geometric units so as to permit the description of spatial variability in a meaningful manner; and
- Assignment of parameters (values and/or statistical distributions) to the defined geometric units.

It is anticipated that, in a similar way to the approach adopted by SKB and Posiva, the integrated Site Descriptive Model will be divided into parts comprising clearly defined disciplines which may form either chapters or discipline-based models. The discipline-based models that are likely to be developed for UK sites comprise the following:

- Geology;
- Hydrogeology;
- Hydrochemistry;
- Geotechnical;
- Transport properties;
- Thermal properties; and
- Biosphere.

The Site Descriptive Model will provide the understanding of the characteristics of the site, sufficient to allow further qualitative and quantitative modelling to be undertaken as part of the development of the Environmental Safety Case.

## 1.2 OVERALL WORK PACKAGE OBJECTIVES

This report forms part of a work package which provides RWMD with an authoritative account of:

1. The processes and tools that have been used on international radioactive waste management programmes for processing, interpreting and modelling the data acquired through site characterisation;
2. Any additional processes and tools that are used in other sectors for processing, interpreting and modelling data acquired through site characterisation that may be applicable to a UK-based waste management site characterisation programme.
3. The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in the UK;
4. The extent to which the required resources may vary in response to variations in the geological environment at the site(s) in the UK that are being characterised; and
5. The identification of any gaps in available resources to support a UK-based site characterisation programme.

This report deals with the discipline of geology, with separate reports covering the other scientific disciplines.

## 1.3 APPROACH

This report provides a review of the geological interpretation and modelling methods used in a number of national radioactive waste disposal site investigation. The programmes covered are noted below. They have been chosen to provide sufficient detail to determine the issues associated with the characterisation of various geological environments typical of those that may be selected for the deep geological disposal of radioactive waste in the UK. The three potential host rocks for a UK repository being considered by RWMD are:

- Higher strength rocks - typically crystalline igneous and metamorphic rocks or geologically older sedimentary rocks where any fluid movement is predominantly through discontinuities (e.g. fractures);
- Lower strength sedimentary rocks - typically geologically younger sedimentary rocks where any fluid movement is predominantly through the rock matrix; and
- Evaporites - typically anhydrite (anhydrous calcium sulphate), halite (rock salt) or other evaporites that result from the evaporation of water from water bodies containing dissolved salts.

This study has drawn from experience gained from the following site characterisation programmes.

- Andra, France (mudrock investigations near Bure);
- SKB, Sweden (crystalline rock without cover – Laxemar and Fossmark sites);
- Nirex, UK (crystalline rock with cover – Sellafield and Dounreay);
- WIPP, USA (bedded salt);
- Posiva (crystalline rock without cover – Olikuoto);
- Nagra, Switzerland (both crystalline and mudrock investigations);
- DBE, Germany (salt dome – Gorleben).

The focus of the review is on the first four programmes listed above, with the others used to provide information from a different perspective, for example: bedded salt versus diaperic salt.

The programmes covered have been selected because they have examined geological settings suitable for the siting of a repository that are relevant to the geology of the UK; i.e. similar geological situations may be examined by the British repository programme. These settings are:

- Basement without cover (Sweden (SKB), Finland (Posiva) and Switzerland (Nagra));
- Basement with cover (UK (Nirex));
- Low permeability sedimentary rocks (France (Andra) and Switzerland (Nagra));
- Bedded salt (USA (WIPP));
- Salt dome (Germany (DBE)).

Despite their age, the Nirex investigations, particularly at Sellafield, were a particularly comprehensive site characterisation programme. This is partly because of the basement under sedimentary cover setting, meaning that the sites examined are geologically more diverse than the situations examined by the other programmes and that both basement and sedimentary rocks require detailed characterisation. To achieve this, a wider range of methods were applied than for the other programmes. Despite the vintage of the Nirex investigations, many of the approaches adopted at Sellafield would still be applicable in a similar investigation today; a comprehensive review of this work is provided here. While some of the approaches, data processing methods, computing capacity and modelling software have advanced significantly since the end of the Nirex investigations in 1997, the range of techniques used and their application is still relevant to a new UK programme. To avoid considerable duplication, shorter summaries have been provided of the other programmes; in particular, highlighting any differences in approach and techniques used.

### 1.4 OBJECTIVES FOR GEOLOGICAL INTERPRETATION AND MODELLING

Information on the geology of the site is required both to provide a framework for the preparation of the other descriptive models and to provide confidence in the understanding of the site within the broader geoscientific stakeholder group has been defined by Nirex (2005). The information required to compile the Geology discipline-based model comprises the following:

- The topographic form of the site and its environs to provide the framework within which the investigations and the disposal facility are located;
- The geomorphology of the site and its environs as an aid to interpreting the Quaternary history of the development of the site and the superficial distribution of the geological materials present at the site;
- The nature, distribution and properties of the soils (drift deposits);
- The nature, distribution and properties of the sedimentary cover rocks present at and around the site;
- The nature, distribution and properties of the host rock formation within which it is proposed to construct the waste vaults should a disposal facility be constructed at the site;
- The nature and characteristics of the structural geological features present at the site including folds, faults, bedding planes, joints, etc together with an assessment of the manner in which the various features will be described (stochastically or deterministically);
- The nature, extent, distribution and history of exploitation of mineral deposits within the area;
- The qualitative and quantitative assessment of the spatial heterogeneity of the geological units present at the site together with an assessment of how this heterogeneity can be represented within models of the site;

- The geological evolution of the area with the aid of geochronological studies, the genesis of the fracture-filling materials and studies of the movements along faults and fracture surfaces; and

- The tectonic stability of the site with the aid of seismological monitoring, palaeoseismic analysis and kinematic analysis.

Full details of the information requirements of a geological discipline-based model are provided in Appendix A of Nirex Report 123 (Nirex; 2005).

## 1.5 REPORT STRUCTURE

This report is divided into 5 main chapters followed by the conclusions and references. Each chapter finishes with a brief summary in the context of the overall objectives as outlined in Section 1.2.

**Chapter 2 'Context of International Programmes'** briefly summarises the type of waste, repository and geology investigated which are being considered by programmes in the UK (Section 2.1), France (2.2), Sweden (2.3), Finland (2.4), USA WIPP (2.5), Germany – Gorleben (2.6) and Switzerland (2.7). It thus provides the context for addressing the objectives as outlined in Section 1.2.

**Chapter 3 ' Approaches to Interpretation and Modelling'** then details examples from these programmes with the aim of addressing the first objective detailed in Section 1.2 namely the inclusion of 'The processes and tools that have been used on international radioactive waste management programmes for processing, interpreting and modelling the data acquired through site characterisation'.

> **Section 3.1** examines the application of interpretation and modelling in the **UK Nirex Sellafield example** with respect to mapping (topographical, geomorphological and geology) addressed in Section 3.1.2; and the nature, distribution and properties of 'Basement' rocks in 3.1.3, Sedimentary rocks in 3.14 and superficial (drift) deposits in 3.1.5. The application of interpretation and modelling to the overall geological structure is then described in section 3.1.6 and mineral deposits in 3.1.7. The geological spatial heterogeneity is then addressed in section 3.1.8 with an interpretation of structural domains and logging of potentially flowing features in 3.1.9 and 3.1.10. Tectonics of the example are described in 3.1.11. As part of the planning for the sinking of the Rock Characterisation Facility shafts at Sellafield Nirex undertook a series of predictions of geological (and other) characteristics that would be encountered in the shafts which are described in Section 3.1.12. A summary of the approaches used in the Sellafield example is then provided in Section 3.1.13.
>
> **Section 3.2** examines the application of interpretation and modelling in the **SKB Forsmark and Laxemar examples**. Section 3.2.1 addresses mapping (topographical, geomorphological and geology); with the nature, distribution and properties of 'Basement' rocks and superficial (drift) deposits discussed in 3.2.2 and 3.2.3. The application of interpretation and modelling to the overall geological structure (3.2.4) is then described in Section 3.2.5 with a detailed discussion on modelling at regional and local levels in Sections 3.2.6 and 3.2.7. Mineral deposits interpretation is provided in Section 3.2.8. The geological spatial heterogeneity is then addressed in section 3.2.9 with visualisation discussed in Section 3.2.10 and tools used for logging described in 3.2.11. A

summary of the approaches used in the Forsmark and Laxemar example is then provided in Section 3.2.12.

**Section 3.3** addresses the application of interpretation and modelling in the **Posiva Olkiluoto example**. Sections 3.3.1 and 3.3.2 respectively describe the nature, distribution and properties of Basement rocks and superficial (drift) deposits. Mineral deposits are noted in Section 3.3.4 and a summary of approaches used and their application is provided in Section 3.3.5.

**Section 3.4** addresses the application of interpretation and modelling in the **Andra Bure example** with respect to mapping (topographical, geomorphological and geology) addressed in Section 3.4.2; and the nature, distribution and properties of sedimentary rocks in 3.4.3 and superficial (drift) deposits in 3.4.4. The application of interpretation and modelling to the overall geological structure is then described in Section 3.4.5 and mineral deposits in 3.4.6. The geological spatial heterogeneity is then addressed in Section 3.4.7 with visualisation discussed in Section 3.4.8. A summary of the approaches used in the Bure example is then provided in Section 3.4.9.

**Section 3.5** addresses the application of interpretation and modelling in the **Nagra Opalinus Clay example** with respect to mapping (topographical, geomorphological and geology) addressed in Section 3.5.2; and the nature, distribution and properties of sedimentary rocks in 3.5.3. The geological spatial heterogeneity and geological evolution are then addressed in Sections 3.5.4 and 3.5.5 and a summary of the approaches used in the Opalinus clay example is then provided in Section 3.5.6.

**Section 3.6** addresses the application of interpretation and modelling in the **BGR Gorleben example** with respect to mapping (topographical, geomorphological and geology) addressed in Section 3.6.1; and the nature, distribution and properties of sedimentary rocks in 3.6.2 and superficial (drift) deposits in 3.6.3. The application of interpretation and modelling to the overall geological structure is then described in Section 3.6.4 and mineral deposits in 3.6.5. The spatial heterogeneity and geological evolution of the example are then addressed in Sections 3.6.6 and 3.6.7. A summary of the approaches used in the Gorleben example is then provided in Section 3.6.8.

**Section 3.7** addresses the application of interpretation and modelling in the **DoE WIPP example** with respect to mapping (topographical, geomorphological and geology) addressed in Section 3.7.1; and the nature, distribution and properties of sedimentary rocks in 3.7.2 and superficial (drift) deposits in 3.7.3. The application of interpretation and modelling to the overall geological structure is then described in Section 3.7.4 and mineral deposits in 3.7.5. A discussion on the interpretation of the tectonics of the example is given in Section 3.7.6 and a summary of the approaches used in the DoE WIPP example is then provided in Section 3.7.7.

**Chapter 4 'Other Sectors'** examines the application of various technologies and techniques in other sectors, including hydrocarbon exploration/exploitation, for the interpretation and modelling of geological information. This is particularly applicable to sedimentary environments. This chapter addresses the second objective as outlined in Section 1.2 namely the inclusion of 'Any additional processes and tools that are used in other sectors for processing, interpreting and modelling data acquired through site characterisation that may be applicable to a UK-based waste management site characterisation programme. It also addresses, but to a lesser extent, the third objective 'The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in the UK'.

**Chapter 5 'Resources'** provides a summary of the tools for geological interpretation and modelling that could be used in undertaking a site characterisation programme. It also provides information on the potential availability of expertise to use such tools. The chapter addresses the third objective as outlined in Section 1.2 discussing 'The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in the UK'. It also partially addresses the final objective 'The identification of any gaps in available resources to support a UK-based site characterisation programme'.

**Section 5.1** describes the availability of 3D modelling hardware and software.

**Section 5.2** addresses the availability of GIS software.

**Section 5.3** details geophysical hardware and software availability.

**Section 5.4** then describes the availability of the necessary expertise to conduct the early stages of a site investigation programme.

**Chapter 6 'Geological modelling – Tools for interpretation and modelling** summarises the tools and approaches that have been used by national radioactive waste disposal programmes reviewed (Chapter 3) and the other sectors considered in Chapter 4. It identifies the tools and methods that have been used in the programmes and sectors reviewed that could be applicable in a new UK site investigation programme. It thus addresses all the objectives identified in Section 1.2 but particularly the final objectives as outlined in Section 1.2 'The extent to which the required resources may vary in response to variations in the geological environment at the site(s) in the UK that are being characterised'; and 'The identification of any gaps in available resources to support a UK-based site characterisation programme'.

**Section 6.1** addresses geological modelling and interpretation methods and tools.

**Section 6.2** discusses developments in other sectors relevant to a new UK programme.

**Section 6.3** discusses the implications for specific host rocks.

**Section 6.4** then describes an approach for interpretation and modelling of data arising from a UK site investigation programme including site specific factors.

The **Conclusions, Chapter 7** summarise the key findings from each chapter in the context of the overall objectives as stated in Section 2.1.

# 2 Context of International Programmes

This chapter summarises the type of waste, repository and geology investigated which are being considered by programmes in the UK (Section 2.1), France (2.2), Sweden (2.3), Finland (2.4), USA WIPP (2.5), Germany – Gorleben (2.6) and Switzerland (2.7). It thus provides the context for addressing all the objectives as outlined in Section 1.2 and sets the scene for the next chapter which discusses specific examples from each of these national programmes.

## 2.1 UNITED KINGDOM

At the time of the Nirex Sellafield and Dounreay investigations the then repository project was to find a site for the disposal of Intermediate Level Waste (ILW) and certain long-lived Low Level Waste (LLW). High Level Waste (HLW) and other materials such as spent fuel were not then being considered for deep geological disposal. The Nirex repository concept design was for the packaged waste (in a variety of containers depending on the waste type) to be stowed into large rock-cut vaults and surrounded by a cement-based back-fill material.

It should be noted that under the current MWRS Programme, HLW and some spent fuel, as well as the ILW and long-lived LLW is now included in the inventory for deep geological disposal; other nuclear materials, such as plutonium and depleted uranium, may also be considered for disposal in a UK repository.

Sellafield lies on the coastal plain of Cumbria in NW England. Immediately to the east are the rugged uplands of the Lake District National Park.

Between 1989 and 1997 Nirex drilled a total of 29 deep boreholes in the Sellafield area. The first suite of boreholes was drilled to improve the overall geological understanding of the area. Later boreholes were drilled for a variety of specific purposes, such as to gain greater understanding of fault zones or hydrogeology and for Rock Characterisation Facility (RCF) engineering design purposes. In addition to the boreholes drilled by Nirex, a number of older boreholes, drilled for iron ore exploration purposes, were found and re-opened by Nirex. Shallow boreholes were also drilled during the programme for the characterisation of the Quaternary glacial sediments and drill site civil engineering purposes.

Structurally, the site occupies a transitional zone between the western margin of the Lake District Block (which comprises Ordovician to early Devonian basement rocks) and the East Irish Sea Basin which lies mainly offshore and contains up to 8 Km of younger Mesozoic sedimentary rocks.

The potential repository host rock at Sellafield was within the Borrowdale Volcanics Group (BVG), a succession of shallow marine and sub aerial volcanic rocks of mid-Ordovician age forming part of a Palaeozoic basement horst. These rocks crop out in the north-east of the site area and are surrounded by an unconformable cover sequence of younger sedimentary rocks that dip away from the horst structure.

The top surface of the BVG dips to the south-west and at the south-west corner of the Site it lies at a depth of 1600 m. Here it is overlain unconformably by Carboniferous strata, principally limestone, succeeded by the Permian strata of the Brockram Breccia, the St. Bees Evaporites (mainly dolomite and anhydrite) and the St Bees Shales (fine-grained sandstones, mudstones and siltstones) passing up into the Triassic sandstones of the Sherwood Sandstone Group.

The former potential repository zone is bounded by three major faults, the Lake District Boundary Fault, the Seascale-Gosforth Fault Zone and the Fleming Hall Fault Zone. South of the site, the throw of the Lake District Boundary Fault exceeds 1.5 Km and, together, the Lake District Boundary and the Seascale-Gosforth Fault Zones define the boundary of the onshore extension of the East Irish Sea Basin (Akhurst et al., 1997; NIREX, 1997a).

## 2.2 FRANCE

In France it is Government policy for disposal of ILW and vitrified HLW in a deep geological repository. The French programme, subject to final approvals, is for the construction of a deep geological repository in a thick clay (mudstone) bed in the eastern Paris Basin at a depth of about 500m. HLW will be emplaced in large diameter (ca. 70 cm) boreholes drilled horizontally from the repository galleries incorporating bentonite based seals, and the ILW will be disposed of in part of the same facility in larger galleries.

Andra, the French authority responsible for the management of radioactive waste in France, has studied the feasibility of developing a repository for the deep geological disposal of high-level long-lived radioactive (HLLL) Waste. They have considered options for disposal in both clay and granite formations and summarised the results of the two parallel research programmes in two reports published in 2005, Dossier "2005 Argile" covering a clay hosted repository and Dossier "2005 Granite" a ‘granite’ hosted repository (Andra 2005a and 2005b). The former based on a specific site, near Bure on the border between the Haute Marne and Meuse departments, which Andra had been investigating for about 20 years while the latter is based on generic assessments and is not site specific. Only the work at the Bure site is considered here.

The Bure site is situated in the eastern Paris Basin some 250 Km east of Paris. Geologically the area comprises a thick succession of Jurassic strata overlying Triassic strata to the south of the London-Brabant Massif. The Jurassic strata consist of calcareous and clay rich sediments that were deposited in an open and calm marine environment a long way from sediment sources to the north and north-east. The potential repository horizon is the Collovo-Oxfordian clay (COx), which in the vicinity of Bure is from 120 to 160m thick, and has been selected because of its high clay content and low hydraulic conductivity.

There is a graben structure to the east of Bure, the Fosse de Gondrecourt, which forms the eastern boundary of the area under consideration, while to the west and south-west are the Fosse de la Marne and Fosse de Joinville grabens and associated faulting. The area under consideration for a repository has few mapped faults. There is a shallow synclinal structure (the Savonniers-en-Perthois Syncline) in the north of the area.

In 1999 Andra received approval for the development of an underground research facility at Bure and have developed a URL in the COx at a depth of 490m as part of their evaluation of the site. While the URL will not become part of a future repository it is close to the area that is being considered. As part of the work associated with the URL Andra re-evaluated the information from 68 existing boreholes and drilled 40 new boreholes comprising 25 Km drilled length with 3,800 cored metres that were focussed on the characterisation of the COx.

## 2.3 SWEDEN

The Swedish programme plans to dispose of canisterised spent fuel assemblies in large diameter vertical or horizontal boreholes drilled from underground galleries at a depth of about

450 m in Scandinavian Shield basement rocks. The canisters will be sealed into the boreholes using a bentonite-based buffer, and the galleries backfilled with a similar material.

Radioactive waste from the Swedish nuclear power plants is managed by the Swedish Nuclear Fuel and Waste Management Co (SKB). SKB's early work identified that the Swedish crystalline basement rock was, in general, suitable for the geological disposal of radioactive waste. After more than two decades of consultation and preliminary site investigations in eight municipalities, SKB undertook detailed site characterisation at two different locations, Laxemar-Simpevarp and Forsmark in order to identify a suitable location for a geological repository of spent nuclear fuel. SKB have recently (March 2011) submitted permit applications for the construction of a deep geological repository at Forsmark.

The site investigations have been conducted in campaigns, punctuated by data freezes (Page 15 of TR 09-01 (SKB 2000) provides details). After each data freeze, the site data have been analysed and modelling has been carried out with the overall purpose to develop a site descriptive model (SDM). The site descriptive model is then used to inform the design the underground facility and the development a repository layout adapted to the site. It is also essential for safety assessment because the SDM is the only source for site-specific input. Another important use of the site descriptive model is in the environmental impact assessment. The SDM is an integrated model of geology, thermal properties, rock mechanics, hydrogeology, hydrogeochemistry, bedrock transport properties and a description of the surface system.

The Forsmark area is located in northern Uppland within the municipality of Östhammar, about 120 Km north of Stockholm. The candidate area for site investigation is located along the shoreline of Öregrundsgrepen. It extends from the Forsmark nuclear power plant and the access road to the SFR-facility, a repository for low- and intermediate level radioactive waste, in the north-west to Kallrigafjärden in the south-east. It is approximately 6 Km long and 2 Km wide. The north-western part of the candidate area was selected as the target area for the complete site investigation work.

The Forsmark area consists of a crystalline bedrock that belongs to the Fennoscandian Shield, one of the ancient continental nuclei on the Earth. The bedrock at Forsmark in the south-western part of this shield formed between 1.89 and 1.85 billion years ago during the Svecokarelian orogeny. It has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale, ductile high-strain belts and more discrete high-strain zones. Tectonic lenses, in which the bedrock is less affected by ductile deformation, are enclosed between the ductile high strain belts. The candidate area is located in the north-westernmost part of one of these tectonic lenses. This lens extends from north-west of the nuclear power plant south-eastwards to the area around Öregrund. The brittle deformation has given rise to reactivation of the ductile deformation zones in the colder, brittle regime and the formation of new fracture zones with variable size.

The current ground surface in the Forsmark region forms a part of the sub-Cambrian peneplain in south-eastern Sweden. This peneplain represents a relatively flat topographic surface with a gentle dip towards the east that formed more than 540 million years ago. The candidate area at Forsmark is characterised by a small-scale topography at low altitude. The most elevated areas to the south-west of the candidate area are located at c. 25 m above current sea level. The whole area is located below the highest coastline associated with the last glaciation, and large parts of the candidate area emerged from the Baltic Sea only during the last 2,000 years. Both the flat topography and the still ongoing shoreline displacement of c. 6 mm per year strongly influence the current landscape.

The SDM compiled for Forsmark presents an integrated understanding at the completion of the surface-based investigations, which were conducted during the period 2002 to 2008. This is detailed in SKB report TR08-05 (SKB; 2008).

## 2.4 FINLAND

The Finnish programme is similar to the Swedish one with plans to dispose of canisterised spent fuel assemblies in large diameter vertical or horizontal boreholes drilled from underground galleries at a depth of about 600 m in Scandinavian Shield basement rocks. The canisters will be sealed into the boreholes using a bentonite-based buffer, and the galleries backfilled with a similar material.

Posiva is the nuclear waste management organization in Finland and is responsible for research into the final disposal of spent nuclear fuel and for the construction, operation and eventual backfilling and closure of the final disposal facility. The site selection process for an HLW repository started in 1983 with a country-wide survey of the principal geological features of Finland, primarily of bedrock.

In 1999, Posiva applied to the Finnish government for a policy decision on developing a repository for spent fuel at Olkiluoto, a nuclear power plant site. Both Kauppa-ja teollisuusministerio (KTM – the Finnish Ministry of Trade and Industry) and Sateilyturvakeskus (STUK – the Finnish Radiation and Nuclear Safety Authority) approved the EIA for the final disposal of spent fuel from Loviisa and Olkiluoto at Eurojoki on the Olkiluoto site. The Eurojoki municipality supported the application and the next stage required a decision in principle from the Finnish Council of State, which was necessary prior to the development of an underground laboratory. In 2001 the Finnish parliament ratified the government's Decision in Principle to accept Posiva's application to locate the repository at Olkiluoto at a depth of between 600 and 650 m in the crystalline bedrock.

The Olkiluoto site, approximately 7 $Km^2$ in the municipality of Eurajoki on the coast of SW Finland, occupies the western half of Olkiluoto Island and is adjacent to the nuclear power station. The regional geological setting is the Fennoscandian Shield, comprising schists and gneisses intruded by tonalites to gabbros and younger, deep (2 - 5 Km) Rapakivi type granites. The youngest rocks present are olivine diabases intruded as dykes and sills. The island itself comprises a migmatised mica schist (occasionally mica gneiss) with some amphibolitic inclusions and lenticular and plate-like intrusions of tonalite-granodiorite composition. To the east occurs an un-metamorphosed sandstone graben deposit up to 1800 m thick.

The site has low relief (15 m) and is largely covered by soils, typically sandy till with some rocks and boulders, between 2 - 5 m thick. Clays and peat deposits are rare. There are three main fracture trends and these may be distinguished topographically as elongated depressions formed by preferential erosion along the fracture zones. The fractures are mainly steeply dipping but may also be horizontal. Most are tight or filled with calcite, kaolinite, illite and pyrite, but some are open. Typical of crystalline, hard rock environments, the intensity of fracturing decreases with depth.

Site characterisation activities at Olkiluoto have been taking place for the past 20 years by means of ground- and air-based methods and with shallow and deep boreholes. Work has also been undertaken at the ONKALO rock characterisation facility at Olkiluoto the construction of which started in 2004. There is an increasing level of confidence in the Olkiluoto site description although investigations are still continuing to further characterise bedrock properties and groundwater characteristics. A series of Site Reports have been produced with the third version published in 2009 (Posiva; 2009). This version has developed an updated version of the descriptive model of the site which describes the geometry, properties of the bedrock and the water and associated interacting processes and mechanisms (Posiva; 2009).

## 2.5 USA – WIPP

The WIPP site is located about 30 miles east of Carlsbad in south eastern New Mexico, in the Pecos Valley Section of the Great Plains Physiographic Province. Geologically, it forms part of the Delaware Sub-basin of the Permian Salt Basin, which extends over part of five states.

The facility is the only operating deep geological disposal facility considered in this report having accepted its first waste in 1999 following certification by the US Environmental Protection Agency for the storage of transuranic radioactive waste after about 25 years of study and evaluation. It accepts packaged (in a variety of containers depending on the waste type and source) transuranic waste. The waste is disposed of into 'rooms', constructed from galleries, within the Salado Formation bedded halite (rock salt - sodium chloride) at a depth of 655m. These are backfilled with crushed salt.

The ground surface of the site slopes gently from east to west, from an elevation of 1,088 meters above sea level at its eastern boundary to 990 meters above sea level along its western boundary. The area is characterised by a high plains desert environment. The terrain throughout the province varies from plains and lowlands to rugged canyons. Because of the seasonal nature of the rainfall, most surface drainage is intermittent. The Pecos River, 20 kilometres southwest of the WIPP boundary, is a perennial river and the main drainage for the region.

Principal site selection criteria for the WIPP Delaware Basin site were avoidance of pre-existing boreholes, avoidance of the dissolution front of evaporite deposits, and avoidance of the Capitan Reef (a permeable limestone). The major effort was to find a site that was at least one mile from any existing borehole that might affect the groundwater flow at the repository. This distance was based on analysis, which indicated that dissolution of the salt by water flowing through an inadequately plugged borehole through the Salado Formation would not progress a mile from its source in 250,000 years.

Geologically the WIPP site it is located in the northern part of the Delaware Sub-Basin, a structural basin underlying present-day south-eastern New Mexico and western Texas and containing a thick sequence of sandstones, shales, carbonates, and evaporites (salts) of Permian age, and capped by Triassic rocks.

The upper Permian succession is thickest in the northern part of the Delaware Sub-Basin where it comprises in upwards sequence the Castile, Salado, Rustler and Dewey Lake Formations. The WIPP repository is located, at depth, in the lower part of the Salado Formation. The Castile Formation is underlain by the Bell Canyon Formation.

## 2.6 GERMANY – GORLEBEN

The Gorleben salt dome has been investigated for the disposal of vitrified HLW and spent fuel. Galleries and boreholes, at a depth of around 840m, using crushed salt as a backfill would be utilised if a salt dome option is accepted as the way forward for the disposal of German waste.

Located in the Lüchow-Dannenberg district of Lower Saxony, Germany, the Gorleben salt dome, was investigated from 1979 to June 2000 as a potential geological repository for high level (heat generating) radioactive waste (BMWi; 2008) at a planned depth from about 840 m below sea level, and to depths of 150 below this level. The site area is about 25 Km square, covers a surface area of about 475 Km$^2$ and is bounded by the rivers Locknitz (to the north), Jeezel (to the west) and the Lucie Channel (to the south).

Exploration at the Gorleben site was suspended in on October 1, 2000 following a moratorium that was agreed upon by the Federal Government and the energy supply companies. As a consequence of the cessation of exploration activities, a comprehensive and firm assessment of the suitability of the salt dome as a potential repository for radioactive waste could not be confirmed at the time.

The Gorleben Salt Dome and adjoining rim synclines (downfolds) has a north-east to south-west trend extending about 30 Km diagonally across the region. South-west of the Elbe, in the Gorleben area, the Gorleben-Rambow salt dome has a width of about 3.5 Km to 4 Km, narrowing to 1.5 Km to 2 Km south of the Elbe and widening back to 3.5 Km at Rambow. Only the Gorleben salt dome was investigated in detail as a repository site. The Gorleben Salt Dome, itself, is about 14 Km long and about 4 Km wide

The salt dome rock comprises mostly Zechstein evaporite rocks largely comprising halite (rock salt) and a number of other evaporite minerals. The Gorleben dome has a thin cap rock of gypsum, which formed during the Quaternary. The Zechstein salt overlies red mudstone and sandstone of Early Permian age. The halite salt deposits were deposited in an evaporating inland basin known as the Zechstein Basin during the Permian Period (299 -251 million years ago). The original salt deposits had a thickness of more than 1,000 m, but as a result of gradual gravitational flow (halokineisis) to form the Gorleben and adjacent Rambow domes, it has only a residual thickness of about 100 m to 500 m outside of the mushroom-shaped salt domes. The mobile salt migrated laterally and vertically during geological time to the dome centres where the salt rock thickness is in the region of 3000 m to 4450 m. The upper boundary between the salt formation and the overlying gypsum cap rock at Gorleben lies at depths between 230 m and 341 m below sea level.

Because of marked uplift and a long deformation history the evaporate deposits of the salt dome take the form of a halotectonic breccias, with primary sedimentary feature mostly destroyed or homogenised by fracturing and rehealing during uplift. In general, the Gorleben Hauptsalz halite body is composed of halite crystal lumps with a matrix of fine- to medium-crystalline halite with anhydrite impurities. Mixed evaporate salts including, halite, potash, carnalite, kieserite, polyhalite and anhydrite may be present in some of the associated salt bodies, and in the overlying and underlying beds.

The salt deposits, where not disturbed by halokineisis, are overlain by Triassic Bunter sandstone and mudstone ranging in thickness from about 800 m to 1500 m and lying at between 3000 m and 4300 m below sea level. During the Late Triassic Keuper, salt flow increased forming the diapirs of Domitz and Aulosen to the north–west and south-east of the Gorleben-Rambow structure, respectively. During the Jurassic Period (199 to 145 million years ago) the salt continued to migrate from the margins to the centre of the dome (pillow) so that Jurassic rocks were eroded and are only present in the adjacent synclinal down folds. The diaper structure of the Gorleben-Rambow continued to migrate and grow until the end of the Cretaceous Period (65 million years ago).

The Zechstein evaporite beds of the target repository area of the salt dome is a highly deformed mixed layer deposit comprising halite (rock salt - sodium chloride); anhydrite (anhydrous calcium sulphate); kieserite (magnesium sulphate) and carnallite (potassium magnesium chloride) with thin beds of limestone.

Sedimentary rocks overlying the salt dome include thin relics of Cretaceous age, but mostly comprise sedimentary rocks and unconsolidated deposits of Tertiary and Quaternary age. By the Tertiary upward diapiric growth of the dome diminished greatly. Overlying Tertiary-age sediments include sand, silt and clay deposited in marine and continental environments. These Tertiary sedimentary rocks were affected by less intense halokinetic (salt doming) uplift of the Gorleben-Rambow salt dome during their deposition from about 61 to 20 million years ago. Gravitational uplift of the salt resulted in a thickness of 50 m to 200 m of Tertiary sediments above the dome, compared to thicknesses of up to 1100 m in the adjacent subsiding (down-warped) synclines.

## 2.7 SWITZERLAND

Deep geological disposal is the preferred option for the management of higher activity (HLW and some ILW) and spent fuel in Switzerland. The Swiss concept for safe storage of radioactive waste proposes two deep geological storage facilities; one for high-level waste and long-lived intermediate-level waste (HLW/ILW), and another for intermediate and low-level waste (I/LLW). Potential sites have not yet been selected but both 'granite'- and clay-hosted sites have been investigated, and URLs developed in both rock types.

The Swiss Government has recently (1st December 2011) approved Nagra's proposed six siting regions as potential host regions for a geological repository for low and intermediate radioactive waste and a geological repository for high-level radioactive waste. This decision completes Stage 1 of their Sectoral Plan and gives Nagra approval to commence Stage 2 of the plan, the commencement of investigation at the six siting regions to identify the site of the Swiss HLW/ILW and I/LLW repositories hosted in clay. All six of the sites will be evaluated for the latter and three for the former.

The six sites are:

- Jura Ost (HLW/ILW and I/LLW)
- Jura-Südfuss (I/LLW)
- North of Lägern (HLW/ILW and I/LLW)
- Südranden (I/LLW)
- Wellenberg (I/LLW)
- Zurich Nordest (HLW/ILW and I/LLW).

Apart from Wellenberg, which is in central Switzerland, all of these siting regions are in the north of the country. All of these siting regions avoid the tectonically active Alpine area of Southern Switzerland.

In 1980 a regional geological investigation programme was initiated in Northern Switzerland with the goal of identifying potential sites for further investigation as potential HLW repository host rocks.

The crystalline basement of Northern Switzerland was selected as the first priority for further investigation. The crystalline basement was considered by Nagra to offer good potential as a host rock because it is well consolidated, geologically stable, an area of low seismicity, and granite and gneiss (hard crystalline rocks) are favourable from an engineering point of view.

However, since 1988, both lower strength sedimentary rocks (for HLW) and hard crystalline rocks (as a possible host rock for ILW) have been considered by Nagra. The focus has now moved to another geological unit, the Opalinus Clay, which is a part of the sedimentary rock succession overlying the crystalline basement in Northern Switzerland and it is these investigations that are summarised in this report.

In an effort to characterise the potential host rocks, Nagra has conducted regional and site specific surveys and drawn on a number of techniques which serve as tools to collect data to feed into an overall geological model, which will allow modelling of both bedrock structure and groundwater movement. These tools include; geological mapping and borehole logging, geophysical surveys, hydrogeological, chemical, mineralogical and rock mechanics studies.

The crystalline basement of Northern Switzerland is essentially an extension of the Black Forest basement in Germany; therefore mapping studies on exposure of the basement in the Black Forest were undertaken as an analogue study. It is covered by a series of sedimentary formations ranging in age from the Palaeozoic to the Quaternary (recent). The basement itself consists of metamorphic gneisses (mainly metapelites and meta-greywackes) which have undergone high-grade metamorphism, and have been intruded by Variscan (340-280 Ma) granites and dykes (Nagra 1994b, NTB 93-12).

Geological investigations were expanded in 1988 to include sedimentary formations and an initial assessment of the sedimentary succession for potential storage options was outlined in Nagra 1988, NTB 88-25, which narrowed down the options to identify the Opalinus Clay, Brauner Dogger and Effingen Beds/Member, and Helvetic Marl as potential host sedimentary units for a deep geological repository. It was concluded that the Opalinus Clay provided the most promising option, and 5 potential siting options were identified, with the Opalinus Clay (with potentially the stratigraphically adjacent Effingen Beds and Brauner Dogger sequences partially included) as the proposed host unit.

The Opalinus Clay is a homogenous claystone formation that is c. 180 million years old. It was deposited uniformly across Northern Switzerland. A benefit of this uniform distribution is that properties of the clay in one location can be inferred to be similar in other locations within the unit (Nagra 2002a). It ranges in thickness from 70 – 120m thick. It is stratigraphically overlain by the Brauner Dogger sequence and Effingen in a continuous sedimentary succession which is shallowly dipping to the SE. (Nagra 2002d, NTB 02-03). At the potential siting locations in North Switzerland the Opalinus Clay occurs at a depth ranging from about 200m to 700m.

## 2.8 SUMMARY

These national programmes provide a broad selection of geological settings, including:

- Basement without cover (Sweden (SKB), Finland (Posiva) and Switzerland (Nagra));

- Basement with cover (UK (Nirex));
- Low permeability sedimentary rocks (France (Andra) and Switzerland (Nagra));
- Bedded salt (USA (WIPP));
- Salt dome (Germany).

The programmes covered have been selected because they have examined geological settings suitable for the siting of a repository that are relevant to the geology of the UK; i.e. similar geological situations may be examined by the British repository programme.

# 3 Approaches to Interpretation and Modelling

This chapter details examples from international programmes described in Chapter 2 with the aim of addressing the first objective detailed in Section 1.2 namely evaluating 'The processes and tools that have been used on international radioactive waste management programmes for processing, interpreting and modelling the data acquired through site characterisation'.

## 3.1 THE NIREX SELLAFIELD EXAMPLE

### 3.1.1 Introduction

The Nirex Sellafield investigations are covered in some detail because of the comprehensive suite of methods used and because of the additional complexity of the investigations that the sedimentary cover over the basement potential host rocks geological setting entailed. The Nirex investigations at Dounreay adopted a similar approach to the investigations at Sellafield with an identical suite of acquisition methods and approaches. The termination of the Dounreay investigation programme in 1991 after drilling of the first two boreholes to concentrate on the Sellafield investigations means that the level of interpretation and modelling undertaken at Dounreay was very limited when compared to Sellafield and digital 3D geological models were not constructed.

The Nirex Sellafield investigations between 1988 and 1997 were designed to assess the suitability of the area for development of a deep geological disposal facility of ILW and some long-lived LLW. The programme included the drilling and testing of 23 deep boreholes, the deepest of which terminated almost 2000m below surface, and locating and re examining three old mineral exploration boreholes.

Sellafield lies on the coastal plain of west Cumbria in NW England. Immediately to the east are the rugged uplands of the Lake District National Park. The Nirex study areas are shown in Figure 1.

The investigations were broadly divided into acquisition and interpretation activities. The acquisition aspects, including both new field-based acquisition (mapping, geophysical surveys, borehole drilling etc.) and access to existing information (speculative off-shore seismic data, mineral exploration borehole data etc), provided information for interpretation. The information arising from the investigations was passed to the various Joint Interpretation Teams (JIT). These teams were multi-contractor teams composed of relevant experts with experience in the topics and geologies under consideration with separate teams for 'geology' and 'hydrogeology'. The Geology JIT had responsibility for the integration, interpretation and synthesis of the data arising from the acquisition activities, after completion of any post acquisition processing. This included geological synthesis, 3D geological model development, structural interpretation etc. Data was supplied to the JITs once fully approved. This could be a considerable time after acquisition which meant that any recommendations to fill data gaps, for specialist acquisition or post acquisition processing of data for specific purposes and the subsequent availability of such supplementary data for use by the JIT often took a significant time. The JITs produced a series of reports and updates (which equate to the site descriptive model approach used by SKB) at intervals during the investigations.

The primary objective of the geological element of the Sellafield site characterisation programme was to develop an understanding of the geology of the area. This included:

- Lithostratigraphy;
- 3D structure;
- Faulting;
- Fracturing;
- Quaternary geology

This provided the framework for the assessment most of the evaluations including hydrogeology, hydrochemistry and engineering design.

### 3.1.2 Mapping (topographical, geomorphological and geological)

The assessment of the Sellafield area was undertaken at four, increasingly detailed, scales (Figure 1). These were:

- **Region** - an area of approximately 60 x 55 Km of west Cumbria and the East Irish Sea Basin. This area allowed the more detailed investigations to be understood in the regional context.

- **District** - an area of approximately 35 x 20 Km along the west Cumbria coast centred on Sellafield. This area included all of the catchment areas evaluated in detail. All new data acquisition (geological mapping, Quaternary mapping/characterisation, fracture mapping, off-shore and on-shore seismic surveying, airborne geophysics etc) was undertaken within this area.

- **Site** - an area of 8 x 6.5 Km within the District centred to the southeast of the Sellafield site. All the deep site investigation boreholes and most of the Quaternary investigation trial pits and shallow boreholes were drilled within this area.

- **Potential Repository Zone (PRZ)** - an irregular area of approximately 1 x 1 Km within which the repository would have been constructed. All of the boreholes drilled for the Rock Characterisation Facility (RCF) investigations where collared within this area and the 3D trial seismic survey undertaken included the whole of the surface expression of the PRZ area. Detailed engineering design information was largely acquired within this area.

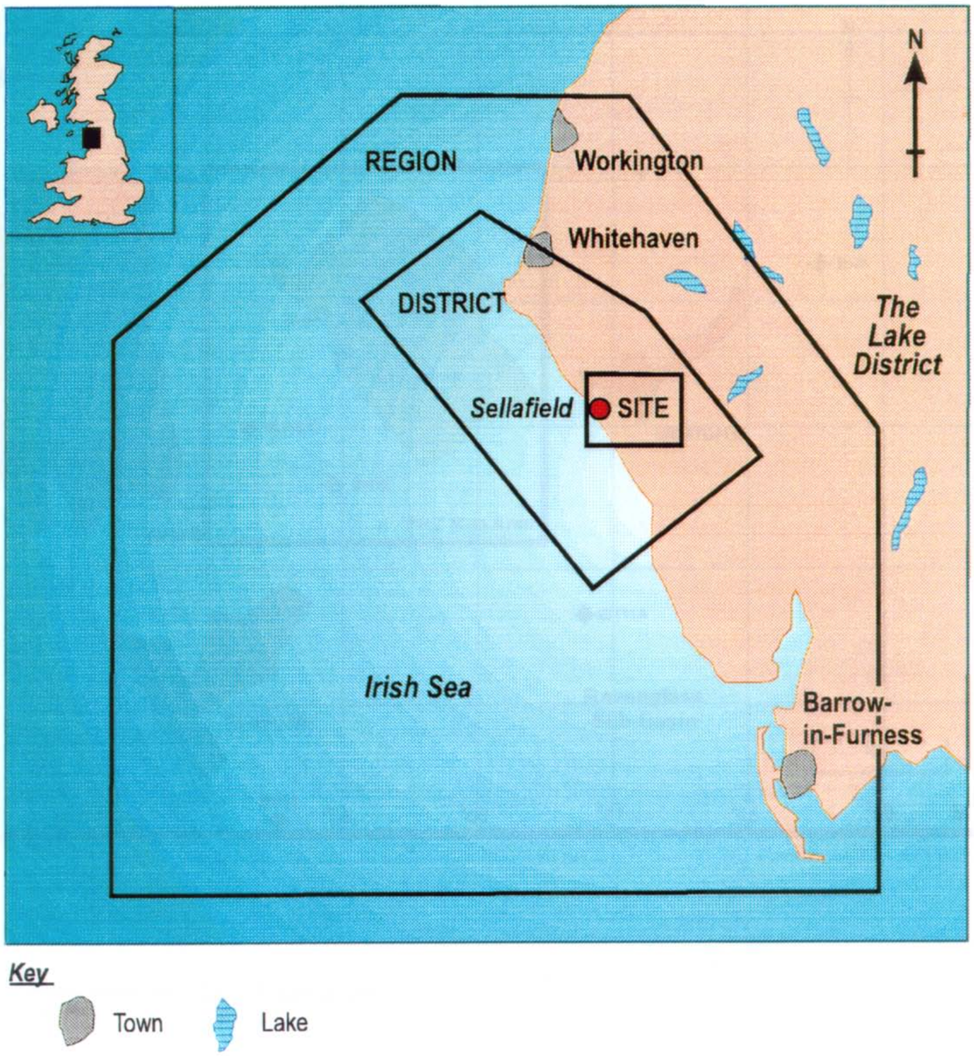



**Figure 1** The Nirex study areas around Sellafield in West Cumbria (from NIREX, 1997a).

Prior to 1992 several generations of geological and subsurface structure contour maps were prepared for Nirex covering various parts of the Sellafield District, often using different or partial data sets. The first maps were derived from the interpretations of the early seismic investigations in the vicinity of the Site (e.g. Chadwick and Holliday; 1988). These were succeeded by two suites of maps covering the larger part of the present District. For the BGS Sellafield Mapping project (Barnes et al.; 1991) maps were based on mapping of the limited surface exposures and subsurface data from boreholes and mine-plans and incorporated the Chadwick and Holliday (1988) seismic interpretation in a part of the area where there were no other subsurface data. Subsequently, the New Seismic Interpretation (J Arthur and Associates; 1991) produced a new set of maps based on interpretation of the geophysical data and although a limited amount of collaboration with the Mapping Project team was possible, there was no opportunity to combine the various datasets to produce a fully integrated 2D geological model. This integration was later done for the Site only (GeoScience 1991), yielding a new set of maps which were different in many respects from those which preceded them. In 1992 the results of these previous studies were integrated to produce a single consistent set of structure contour and geological maps of the Site, District and Region areas (see 3.1.2 below for details) These were subsequently updated as new information became available, primarily from the deep borehole drilling programme during the course of the investigations (e.g. Nirex 1993a, 1995a, 1997b).

The various revisions (reported as 'updates') to the interpretation were undertaken at various times and did not use a formal dated cut of point (c.f. data freezes of SKB) but used what ever data was available to the JIT at the time. Different revisions to Site, District and Region 2D geological models did not necessarily happen at the same time and so utilised different data which at times made consistency a problem.

#### 3.1.2.1 Topography

Digital topographic data for use in the investigations were purchased from the Ordnance Survey (OS). For the District and Region this was at a scale of 1:50,000 and was used as supplied. For the Site area this was at a scale of 1:10,000 which was supplied as map 'tiles' by the OS. For use by the project these were 'stitched' together to provide a seamless digital terrain model (DTM). This process identified an error in the data for one of the tiles which were found to be several metres out in elevation with respect to the adjacent tiles. In conjunction with the OS this was corrected and a seamless 1:10,000 base map was available to the JITs and other users for the Site. For 'blue line' data (stream/river courses and lakes/ponds) the Centre for Hydrology (CH – now Centre for Ecology and Hydrogeology) dataset was used. This is based on the OS 1:50,000 topographic data (but with additional processing) and provides XYZ data along water courses and for fresh water bodies.

Using the same data sources a new DTM was produced in 1997 (Nirex 1997g).

The 1:10,000, once corrected and available as a seamless DTM, and the 1:50,000 data did not require further processing or interpretation for use.

All borehole locations were topographically surveyed while the drill rig was on site and this information used to provide accurate XYZ data for borehole collar location (because of drill platform preparation borehole collar elevation may be several metres different from that derived from the topographic map data) to which all down hole information could be accurately related.

True spatial location (XYZ) was derived for all samples, lithological boundaries and logged features from a combination of the borehole trajectory survey and FMS/FMI and BHTV wireline logs which were matched to planar core discontinuities (fractures, joints, bedding etc.) by inspection (e.g. Rogers; 1994) and used to correct drillers core depths to true vertical depths (see e.g. Rogers and Shaw; 1993). This was a laborious and time consuming process but did allow a number of attributed, spatially located and oriented data sets to be compiled that were used in subsequent analysis. These included fractures, faults, joints, bedding, orientation of test samples (mineralogy, porosity/permeability, engineering geology). It also allowed gross drilling errors, for example an over deepening of BH3 by about 1.25m when the hole was cased into the St. Bees Dolomite or inverted boxed cores to be identified that would otherwise have been unrecorded.

#### 3.1.2.2 Geological Mapping

The area was first geologically mapped in detail (1:10,560 (6" to 1 mile) scale) between 1870 and 1895 and was resurveyed between 1921 and 1937. (Akhurst et al; 1997). At the start of the Nirex investigations the British Geological Survey was in the process of re-surveying the Lake District at a scale of 1:10,000 and was commissioned by Nirex to include the west Cumbria coastal strip between Whitehaven and Ravenglass in this re-survey. Re-surveyed maps at this scale for the whole of the Site were available by 1992 (though these were subsequently revised as data from Nirex investigations became available) and for the whole of District (and most of the Region) by 1996.

Mapping was undertaken by ‘traditional’ methods (field mapping supported by information from previous work, borehole data and any available geophysics) with the additional benefit of new information arising from the early Nirex investigations (seismic and airborne geophysics) and the later revisions benefiting from new deep borehole information and the interpretation undertaken by the Nirex JIT.

Map preparation was undertaken following the then standard BGS procedures using Intergraph software based digital map drafting. Following checking and approval the digital maps were available to the JIT. Many of the BGS field mapping geologists responsible for the mapping and subsequent preparation of the maps were also key members of the JIT having relevant expertise in the geology and structure of the area under investigation at Sellafield. This ensured that their knowledge, gained during their field work but which, for various reasons, was not always represented in the final maps, was available during the work of the JIT.

#### 3.1.2.3 Geomorphological Mapping

Some feature mapping as undertaken during the Quaternary field work programme. This work was interpreted as part of the Quaternary characterisation work carried out at Sellafield (Nirex; 1997b). Again the use of this data was facilitated by those involved in its acquisition playing a significant role in its subsequent interpretation. This included the use of ‘landform domains’ as a tool for the characterisation of large areas of onshore drift deposits (Eaton, 1993).

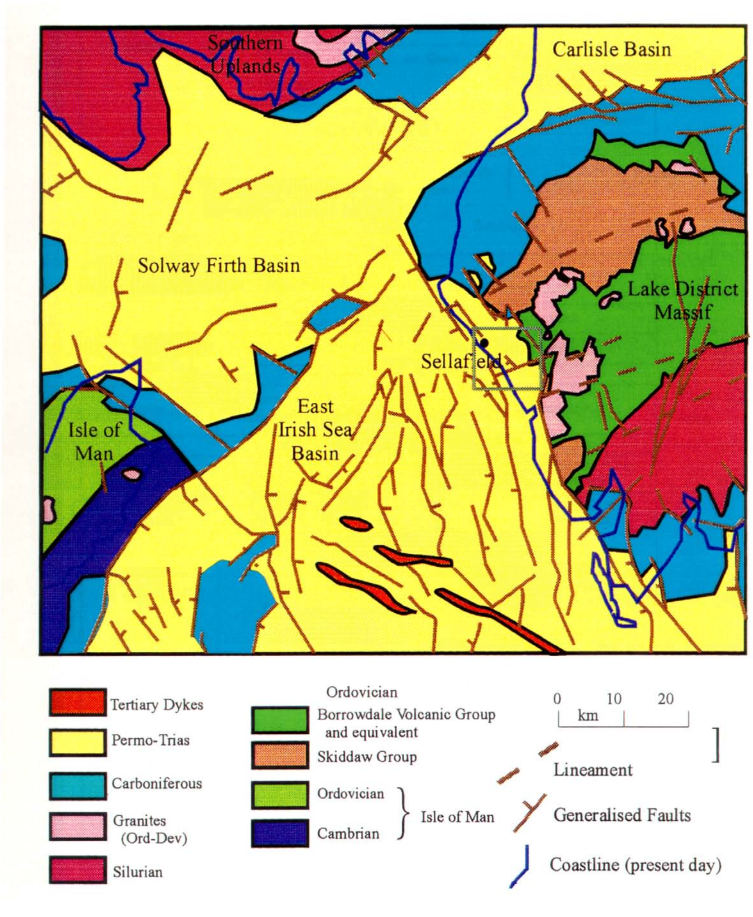



**Figure 2** Generalised structural setting of the Sellafield Study Area (from NIREX, 1997a).

### 3.1.3 'Basement' rocks - nature, distribution and properties

The basement rocks (Borrowdale Volcanic Group – BVG) are not present at surface at Sellafield but are exposed to the east of the Site area. Geological mapping of the western part of the Lake District provided an understanding of their broad distribution, the nature and extent of syn-depositional and volcanogenic faulting, tectonic faulting, fracturing, mineralisation, broad geological structure and metamorphism. The experienced field mapping geologists were used to undertake the geological logging of the borehole cores allowing the extensive knowledge of the rocks at surface to be applied to developing a detailed understanding of the BVG beneath the site.

The logging of the cores in detail, which identified a number of different geological units including tuffs, volcaniclastic sediments, lavas and intrusions, allowed correlation of these units between boreholes and the interpretation of faults. Discontinuity logs for the BVG in the Sellafield, boreholes demonstrate that it is heavily fractured for most of the intersected length.

The Nirex deep exploration boreholes provided significant new stratigraphic and structural information during the JIT interpretation phases. Key data sets used from these boreholes were:

- Core logs (Gibb Deep Geology Group on-site, BGS off-site);
- Core photographs;
- Wireline logs, especially Formation Microscanner/Microimager (FMS/FMI), and Borehole Televiewer (BHTV).

The seismic data were examined on a GeoQuest workstation and estimated bounds of high positional certainty were marked on the sections for all faults noted. Maps were prepared at 1:10000 scale of fault cut certainty. These high certainty bounds were transferred onto the maps for each horizon.

The results of a remote sensing, using aerial photographs at small scale and large scale, as well as satellite imagery, study of the Sellafield Region (GeoScience; 1992), were used to help constrain the positions and orientations of faults at the surface. Lineaments and topographic changes interpreted from these data were compiled to produce a single composite lineament interpretation map for the satellite imagery, and detailed interpretation maps for both scales of aerial photography. Some of the remote sensing lineaments helped to orientate and/or position faults at the surface when compared with field mapping, borehole, and seismic data. The majority of lineaments, however, did not match the other data.

Structural data from the boreholes (fault intersections and orientations where determined) was used to constrain the seismically-imaged fault structures in the vicinity of the boreholes. It should be noted that both data sets contain limitations, in particular the limit of resolution of the seismic data, which affect the degree of confidence that can be placed on any structural interpretations.

Fault rocks or intervals of intense, fault-related fracturing were intersected by the majority of the Nirex Sellafield boreholes. These were identified from the core logs and photographs, supplemented by appropriate wireline log data (density log, array sonic, dipmeter, borehole imagery etc). Faults at a range of scales were intersected in the boreholes. At the upper end of the scale, one or two examples of composite fault zones with several metres of cataclastic fault rock and highly fractured wall-rocks, implying significant displacement (probably >30 m), were encountered in several of the boreholes. Other, smaller-scale structures implying displacement perhaps less than the resolution of the seismic data (probably about 20 m) were also intersected. Thus, the correlation of borehole faults to seismically-imaged faults involved some degree of subjectivity in assessing which were the likely "main" structures. Once faults had been identified in the boreholes, their orientations were determined using the borehole imagery: Formation Microscanner/Microimager and Borehole Televiewer.

At Sellafield the correlation of borehole fault intersections with seismically-imaged structures proved to be relatively straightforward in the cover sequence, reflecting both the relative ease of mapping offset reflectors at and above the cover/basement interface and also the simpler structure of the cover rocks. However, mapping of faults in the BVG from the seismic data is difficult (Chadwick *et al*. 1992) and there is a greater density and complexity of faulting than in the cover.

#### 3.1.3.1 Borehole integration exercise

The aim of this exercise was to integrate the borehole records held by BGS with the seismic data from the onshore Site/District. Prior to drilling new boreholes this borehole data provide the most accurate information available relating to the depth of stratigraphic interfaces and the thicknesses of stratigraphic units. The borehole logs can be used to relate seismic reflectors to lithostratigraphical interfaces as well as constraining the position and dip of fault planes interpreted from the seismic data.

*Methodology*

The BGS borehole archive holds a large number of lithological logs for the Sellafield onshore District. The majority of these boreholes were drilled for iron ore exploration in the Carboniferous rocks beneath the Permo-Triassic cover and, in more northern parts of the District, for coal. The Dinantian Chief Limestone Group was the targeted host for most of the iron ore deposits and thus many logs record continuous sections through the preserved Permo-Triassic and Carboniferous successions to the top of the basement.

One hundred and thirty two borehole records, lying adjacent to (within 200 m) the lines along which the seismic profiles were acquired, were selected for detailed examination in conjunction with the seismic data. Only boreholes which penetrated pre-Quaternary rocks were considered. The density of borehole information is locally variable, with most data coming from the iron ore mining area around Egremont, Haile and Beckermet. Little or no borehole information was available to constrain the seismic interpretation in the western part of the area.

Varying levels of stratigraphical refinement were recorded in the borehole logs, with most detail being given in the Carboniferous succession which was, in most cases, the main area of economic interest for which they were drilled. The Permo-Triassic section was often open-holed into the Brockram and hence the detail given not always accurate. Even when this part of the sequence was cored it may be difficult to recognise boundaries from the logs because of the transitional nature of the contacts. The vertical transition from St Bees Shale into the Sherwood Sandstone and the lateral interdigitation of Brockram in the east, with St Bees Evaporites and Shale farther west, provided particular problems. In areas of interdigitation, St Bees Shale was defined by shale or marl bands exceeding 50% of the total lithology. Where the logs had been previously annotated with stratigraphic divisions by BGS geologists, often after examination of the core, this stratigraphy was accepted.

The stratigraphical data from the borehole records were entered into the BGS Oracle computer database (these will still be held digitally by BGS) to facilitate production of graphic sections, borehole site maps and posted value maps of depth to lithostratigraphical interfaces. Some of the borehole records had previously been entered into the digital database as part of the Geological Structure JIT and Site Integration projects (Nirex 1993b; GeoScience 1991). The depth to each stratigraphic boundary interpreted from the written borehole log is entered into the database. A single lithology is entered against the stratigraphical code (e.g. Brockram was indicated as breccia, Sherwood Sandstone Group as sandstone) to facilitate the ornamentation of graphic logs. A print out showing the lithologies, stratigraphy and thicknesses entered into the database was checked against the original records, and any errors or changes in interpretation noted were amended.

*Borehole cross-sections*

The borehole data were used to construct cross-sections along lines of seismic survey, where data permitted, at 1:4000 scale. Graphic logs of the 132 selected boreholes, and borehole site maps, were produced at that scale. The borehole cross-sections were produced showing the graphic sections 'hung' with respect to ordnance datum. The initial line of section joined the borehole sites rather than extrapolating the borehole data onto the line of the seismic sections. This was done so that raw data, rather than interpretation, was provided for integration with the seismic data. Along-strike extrapolation of borehole data was carried out as part of the integration exercise. The graphic logs and the original cross-sections are archived as supporting documents to the integration exercise.

*Integration*

The position of each of the boreholes was calculated in terms of its nearest common depth point (CDP) position by projecting the location along a line perpendicular to the seismic line where they did not lie upon it. These locations could then be superimposed upon the seismic data on the GeoQuest workstation. The two datasets could not be directly superimposed as the seismic data are represented in two way travel time. However the stratigraphical interfaces picked on the seismic sections were verified against the lithological logs and approximate seismic velocities were used to compare the thicknesses of individual lithostratigraphical units. Fault positions were both checked and modified by comparison with the borehole data. Once the seismic interpretation had been updated using the borehole data the interpretation of each section was sketched onto the borehole cross-sections where feasible.

The principal problems occurred where borehole and seismic data came from the opposite sides of faults. This affected seismic line 90-16 particularly because it runs almost exactly along the line of the Haile Fault for several kilometres and boreholes occur on both sides of the fault plane.

For each horizon, the first priority was to agree a fault pattern to join the District and Region. This was achieved by examining the relevant seismic lines on either side of the boundary and making minor adjustments to fault positions where necessary and where the data allowed. A framework of faults was thereby established between which contours could be joined, wherever possible, with minimal change from their original course.

Depth conversion of the horizons picked from the ‘new’ data in the offshore part of the District was achieved using the same velocity maps that were used by the BGS to construct the Regional maps. However, the results obtained from the drilling of Borehole 3 have required some local modification of the velocity maps in the near-shore part of the District, where recalculation of depths was necessary. This had no bearing on the joining up of maps along the seaward boundary of the District, but did affect the onshore to offshore join, dealt with in more detail elsewhere, and has altered depth contours locally within the District.

#### 3.1.3.2 Onshore/Offshore Integration

Apart from a partially successful transition zone (the area of beach foreshore and shallow marine along the coast) (J. Arthur and Associates 1992) linking on- and off-shore seismic surveys on-shore/off-shore integration had to rely on extrapolation across a data-gap generally of 2 Km or more.

The existing interpretations of the onshore and offshore data were derived from depth conversions using separate velocity maps. Significant discrepancies between the onshore and offshore velocity maps were noted during the Transition Zone interpretation (J Arthur and Associates 1992). In that study, the onshore velocity maps were extended offshore while recognising that this represented only a partial solution to the problem.

A revised contour map of average velocity to the base of Permo-Triassic strata, covering the whole District, was prepared by merging the existing maps. The revision affected only the transition zone and adjacent offshore area. All the seismic lines in this area were depth converted again using the revised velocity maps.

The preliminary onshore and offshore integrated interpretations in the vicinity of the transition zone were copied onto a base map. The interpreted structures and contour patterns were extrapolated into the data gap from both sides. Where insufficient data were available even for a speculative structural interpretation, this has been marked on the maps with `no data'. Areas where structures have been interpreted within the data-gap have been marked with `structure conjectural' on the maps.

#### 3.1.3.3 Surface base fracture mapping

A detailed study of the lithological and discontinuity characteristics of the BVG in two outcrops, at Craghouse Park and at Latterbarrow in Blengdale, was undertaken to provide information relevant to the investigations of these rocks at depth (Nirex; 1997e). The detailed fracture mapping of several hundred square metres of exposed BGG allowed detailed information of fracture characteristics that cannot be determined from logging of borehole cores (or walls), such as lengths, terminations and surface regularity/relief, to be used to enhance the data available from the boreholes.

### 3.1.4 Sedimentary rocks - nature, distribution and properties

The approach adopted by Nirex for the overlying sedimentary rocks in most respects was very similar to that used for the basement rocks described in the section above and is not duplicated here.

In a similar way that the Blengdale outcrop fracture mapping provided data on the fractures in the BVG that cannot be obtained from cores, a study of the sandstones exposed in St Bees Head was carried out to provide information on fractures such as lengths, terminations and surface regularity/relief. In addition to the fracture study the sedimentary architecture of the sandstones was also mapped. This involved the mapping and interpretation of the exposed rocks to determine their depositional environment (e.g. stream channel deposits, overbank deposits, aeolian deposits etc.) leading to the development of conceptual models of the depositional environments of the Permo-Triassic rocks at Sellafield. This understanding was important because of the potential control on groundwater flow that the coarser grained channel fill sediments, the presence of even thin clayey layers and lenses in the overbank deposits and the aeolian layers may have.

### 3.1.5 Superficial (drift) deposits - nature, distribution and properties

Nirex undertook a comprehensive Quaternary characterisation programme in the region up to 25 Km from Sellafield covering most of the on- and offshore parts of the District area. These investigations consisted of:

- Review of previous research;
- Collation and evaluation of data arising from the investigations carried out by British Nuclear Fuels plc in the vicinity of their sites at Sellafield and Drigg;
- Collation and evaluation of data arising from geophysical surveys and boreholes carried out both onshore and offshore by the British Geological Survey; and
- Geophysical surveys, boreholes, trial pits, geological logging of natural exposures and experimental work carried out by Nirex.

The three key objectives for the Quaternary Characterisation Programme were:

- To reconstruct the geological history of the Quaternary in the Sellafield area;
- To provide background information for modelling the near-surface hydrogeological regime; and
- To describe the deformation structures of the deposits and interpret them for evidence of causative mechanisms.

Existing information and new data from 35 shallow (up to 65m deep) boreholes, logging hand and machine dug trial pits and other exposures, geophysical surveys, geological mapping and landform domain mapping was used to develop a detailed understanding of the nature and distribution of the Quaternary deposits in the area. From this understanding a stratigraphic framework for the deposits and a depositional model for the west Cumbria area was developed which formed an important element in the development of a shallow hydrogelogical model for the area (Nirex; 1997b).

Digital 3-D geological modelling was not undertaken for this work because the complex nature of the deposits and their interrelationships was beyond the capability of software (and hardware) at that time to adequately represent. The information was presented as domain maps supported by cross sections with structure contours and isopachites used to represent surfaces and thickness of the major stratigraphic units identified.

The domain maps were used as the basis for the preparation of a series of maps illustrating the main stages of the Devensian glaciation in the area which were responsible for the deposition of the last major phase of Quaternary sediment deposition (Nirex; 1997b).

The Quaternary characterisation programme also included an assessment of deformation and faulting within the drift deposits. This work was largely carried out by interpretation of the on- and off- shore shallow seismic reflection data and information from outcrops such as at St Bees

Head and in a number of small gravel quarries. The visual interpretation of the seismic data identified a number possible neo-tectonic fault structures, glacio-tectonic (glacier push and ice loading) structures, ice melt (kettle hole) structures and gas-escape (pockmark) structures.

The significance of neo-tectonics demonstrating the re-activation existing faults is that it is relevant to assessment of seismic hazard being evidence of fault movement during or since sediment deposition. Three significant neo-tectonic features were identified during the Quaternary characterisation programme, two from seismic interpretation and one from a cliff exposure. Final assessment of these features, including drilling of two shallow boreholes in one of the cases, was that none of them represented fault reactivation (Nirex; 1997c).

### 3.1.6 Geological structure

Modelling of the Sellafield area was undertaken by a multi-contractor group from the JIT using a number of modelling software packages. The approach is summarised here and is provided in more detail in, for example, Nirex report S/97/007 (Nirex 1997h), was that used for the last model iteration for the site in 1996 to produce a consistent geological model of the Site area.

Data sources used included:

- Geological studies of the Sellafield Site area since the May 1995 update;
- An update of the 3D geological structure of the Potential Repository Zone model (reported in Nirex 1995d) based on interpretation of a trial 3D seismic survey ;
- Detailed studies of three fault zones within the Sellafield Site (the Seascale-Gosforth, Fleming Hall and Lake District Boundary Fault Zones;
- Reinterpretation of the north-west and south-east corners of the Site area as part of a more detailed study;
- Data from new boreholes.

For the revision of Site geological model the previous interpretation (Nirex 1995e) was updated by integration of all the studies within, and in the vicinity of the Sellafield Site. It had previously been recognised that the geological maps and sections of the PRZ and Site areas, contained some inconsistencies between the positions of structure contours, geological boundaries and faults. These inconsistencies were a result of the way in which the understanding of the geology of an area was progressively developed. In addition, areas of low data density and areas where no sub-surface information was available were re-assessed.

The final integration of data for the Potential Repository Zone and Site areas was undertaken interactively within three-dimensional digital modelling software. Integration and revision of the structure was made to surfaces at the base of the Calder Sandstone Formation and the base of the Brockram, with additional information from rockhead where necessary. These were input to the modelling software to provide the basic fault and stratigraphic framework of the digital model. Other surfaces were built into the model, from the base Brockram surface, using isopach models of the Carboniferous, Permian and North Head Member Sequences prepared from borehole data. The models were the primary product of the interpretation process from which secondary products, for example maps, cross-sections and two-dimensional slices could be processed.

The three-dimensional models of the Potential Repository Zone and Site areas were constructed using two 3D digital geological modelling systems, VULCAN and earthVision. The two systems employ different approaches to three-dimensional modelling and were used to undertake different tasks during the interpretation of the data and the construction of the models. VULCAN utilises a triangulated mesh system linking irregular raw data points to represent fault and stratigraphic surfaces, whereas earthVision utilises interpolation gridding techniques to define best-fit surfaces. In the Nirex investigations, VULCAN was used to integrate the data and to derive a single integrated dataset for initial interpretation. earthVision was used to construct surfaces where only borehole thicknesses were available and for producing and visualising three-dimensional block models including the distribution in three dimensions of rock and fluid properties. The internal consistency of the models was carried out using 3DMove, a structural restoration software package which allows the visualisation, validation and modelling of geological structures in three dimensions such that there are no gaps or overlaps between modelled blocks.

VULCAN was used to produce a three-dimensional geological model for the Site. Both earthVision and VULCAN were used to produce three-dimensional geological models for the Potential Repository Zone (see Figure 3). 3DMove was tested on earlier versions of the Potential Repository Zone model and was being used to validate independently the current structural models for the Potential Repository Zone and the Site using three-dimensional structural restoration techniques.

The ability to integrate the three-dimensional structural model directly with other aspects of site characterisation and assessment is an important application of geological modelling systems. Within the Nirex investigations the integration involved:

- Geological modelling: this included the integration of data from disparate sources, data verification, testing of alternative interpretations and the construction of three-dimensional block models incorporating lithostratigraphic and structural data;
- Visual and spatial verification of structural and stratigraphic interpretations: the completed three-dimensional model could be transferred directly from one system to another, e.g. from earthVision to 3DMove for verification of the interpretation by volume restoration;
- Attribute or property modelling: includes three-dimensional gridding of geological, hydrogeological and geotechnical data with or without geological control;
- Visualisation: includes the interactive manipulation of three-dimensional block models with rotation, section and plan slicing, peeling and layer removal in order to investigate the structure and distribution of parameters in three-dimensional space;
- Model and data transfer: transfer of models, grids, section and plan data to other modelling applications, for example, in hydrogeology, geotechnics and performance assessment;
- Maps and sections: production of structure contour maps, level plans and cross-sections and three-dimensional visualisations;
- Animated visualisations: visualisations of time series data, for example the results of the Borehole RCF3 Pump Test.

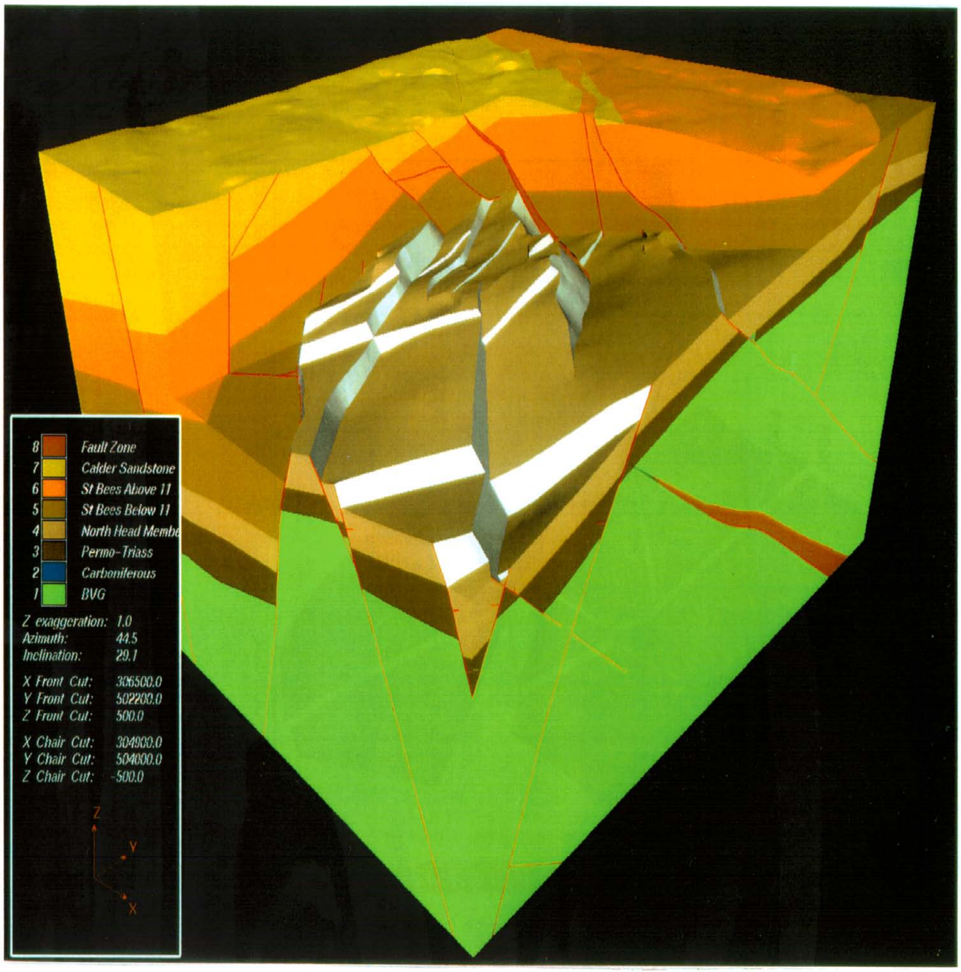



**Figure 3** Block model of the PRZ map area produced using earthVision. The Permo-Triassic sediments have been removed from one quadrant of the model to expose the internal geometry of the basement rocks (from NIREX, 1997a).

At the time (1996) the limitations of the computer modelling software used for the construction of detailed geological models in true three-dimensional spatial co-ordinates included:

- Generalisation: the three-dimensional geological models are usually a generalised representation of the underlying geology. Fault surfaces are commonly represented as smoothed single surfaces rather than as a series of anastomosing strands. Lithostratigraphic surfaces are smoothed; minor faulting is not represented. This is partly a scale issue, as it is impossible to represent all the details of natural variation at the scale of the models. Where possible, in areas of high data density, complex geometries were incorporated into the models, for example fault F2 in the Potential Repository Zone was modelled as a volume rather than as a single surface. In addition, the representation of geology at different scales was addressed by Nirex by the production of several models at different scales.

- Deterministic nature of the model: the three-dimensional models constructed in VULCAN and earthVision are deterministic; they represent one interpretation of the available data for which there may be several alternatives. In order to represent an alternative interpretation a separate three-dimensional model would have been required.

- Traceability of work decisions and assumptions: the construction of three-dimensional geological models is an iterative task involving a significant amount of judgement by the modelling team. The development of logging systems which automatically record every decision made by the operator would be overly restrictive. However the systems do provide some degree of traceability. For example, it is possible to include comments in both VULCAN and earthVision files. Moreover, files describing 'fault trees' in earthVision contain a log of when, and by whom, the files have been modified. Standard work flows are part of the earthVision system.

- Uncertainty: the three-dimensional geological models themselves do not record quantitative information regarding the uncertainty associated with any data used to construct them. Supporting documentation is required in order to provide textual commentary with respect to uncertainties associated with data quality and interpretation.

### 3.1.7 Mineral Deposits

Areas of major mineral resource (coal, hydrocarbons and metal ores) were not present in the Site area examined by Nirex though extensive mineral resources have been exploited in west Cumbria in the past, including just to the north of the Site area where hematite iron ores were exploited to depth of around 300m into the 1980s. As well as the iron ores, exploited in the south as well as the north of the Region, coal has been mined from underground and surface pits in northern part of the District and Region. Nirex wished to avoid areas of mineral resource where possible so as to minimise the risks of future human intrusion (in the event of mineral exploration activities) and reduce the risks of accidently encountering past workings during site investigations or development. One of the reasons that Nirex chose to avoid any area underlain by the Carboniferous Limestone was the potential that it could be assessed for hematite deposits in future because of the known deposits to the north of the site. While choosing to avoid areas with mineral resources Nirex made use of information that was available to them because of ongoing or past mining activities. These are described below.

#### 3.1.7.1 Mineral exploration boreholes

The Site area had been subjected to mineral exploration drilling for iron ore resources and information from the deep boreholes that were drilled prior to the Nirex investigations was available to the programme. Available information included that from lines of boreholes drilled by British Steel in the 1960s between the edge of the Lake District and the coast to explore for iron ore hosted by the Carboniferous Limestone (they were searching, in vain, for a southwards extension of the Egremont-Beckermet mineralisation which has been worked as far south as Calder Bridge). This allowed a preliminary assessment of the deep (pre Permo-Triassic) geology of the Site to be undertaken prior to new data acquisition. This included depth to basement, basement rock type and an understanding of the overlying Permo-Triassic strata. This information was invaluable in aiding the interpretation of the first seismic surveys and the airborne geophysical surveys that were acquired prior to new deep borehole drilling.

Three former iron ore exploration boreholes within and close to the PRZ area were re-located during the site investigations. Two of these (Holmrook 14 and Boonwood) were re-opened during the investigations and geophysically logged. The third (Holmrook 13) was eventually located but the investigations were terminated before it was re-opened and logged.

#### 3.1.7.2 Iron mine plan study

During the work of the JIT a study of the plans of the Beckermet-Egremont-Florence mines was undertaken. These are the workings that are closest to the Site and, at the time of the study, apart from some very small scale shallow extraction of hematite from Florence Mine, were abandoned and largely flooded preventing a physical examination. This study provided two sets of information relevant to the JIT.

Firstly, information from the plans was used to compile thickness and structure information on the Carboniferous Limestone, and to a lesser extent, the overlying Permo-Triassic rocks. This provided geological understanding on the distribution and structure of the Carboniferous Limestone in an area close to the Site which allowed the interpretation of this lithostratigraphic unit to be undertaken in the site area in conjunction with the information from BH3 which was the only borehole to have intersected it at this stage. While the Carboniferous Limestone was not expected beneath the PRZ area (the iron ore exploration boreholes had demonstrated this) the information was important on two counts, one as a potential ion ore resource and the other as a possible karstic aquifer and its proximity to the PRZ was of interest.

The second data set to be derived from the mine plan study was information on fault patterns/network that could be extrapolated into the Site area to 'condition' the interpretation of the structure here. While the information available was not particularly detailed and it probably does not record many minor fault structures, it provided a basis for the interpretation of faulting in the area. Where these data are available the resultant District geological maps are very well constrained.

#### 3.1.7.3 Main Band Colliery fracture mapping

Main Band Colliery was a private mine (now closed) working the Main Band Seam by means of drift access in the area below St. Bees Head. A rapid assessment of the fracturing present in the accessible parts of the mine was made at an early stage of the JIT work to provide information on fracture orientation, mineralisation, displacement etc. to supplement that obtained from the geological mapping programme (the St Bees Head and Crag House Park/Blengdale outcrop fracture mapping work of the St Bees Sandstone and Borrowdale Volcanic Group rocks respectively, was undertaken at a later date). While of relatively limited extent because of access limitations this mapping allowed generation of a spatial fracture data set that could be used in initial interpretation of fracture networks in the Site area. It was local enough to be relevant but had a disadvantage in that the rock units (Lower Coal Measures) are not encountered in the Site area. Despite this problem useful information on fault distribution (spacing, orientation) and fracture networks was made available to the JIT at an early stage in the investigations which could be used in the development of preliminary Site understanding.

### 3.1.8 Spatial heterogeneity

Nirex investigated the parameterisation of the 25 x 25 x 5 m blocks of rock within the PRZ using data from the trial 3D seismic survey and borehole core and wireline derived data (Nirex 1995b and summarised in Nirex 1997d).

For each borehole, the *in situ* rock mass and fluid properties of each identified lithostratigraphic unit were determined from wireline logs, supplemented by direct measurement of rock mass properties on core in the laboratory. Variability in such properties may exist at different scales in any single borehole. From one stratigraphic unit to another, there are often differences in rock mass and *in situ* fluid properties. Within stratigraphic units, properties may be relatively uniform, or there may be a systematic variation in a particular property with depth. Further variability may be superimposed on the succession if the borehole intersects faults or zones of altered or damaged rock.

In addition to the variability seen within each borehole, spatial variability may be expected within each stratigraphic unit throughout the three-dimensional volume of rock. Yet the spatial distribution of rock mass and fluid properties throughout the rock volume cannot be ascertained from borehole data alone. The purpose of the spatial heterogeneity work (Nirex 1997d) was to investigate methods of determining the spatial variability of rock mass and fluid properties throughout the three-dimensional rock volume, by combining borehole-derived measurements with seismic attribute data available from a trial three-dimensional reflection seismic survey.

The first step involved the identification of rock mass properties of importance, and a comparison of the methods used to determine those properties, i.e. laboratory tests on core samples and *in situ* measurements from wireline logs. Data obtained from wireline logs differ from those obtained from core samples in several respects. Not only do they represent *in situ* conditions, which core samples do not, but they are also collected more continuously throughout a borehole than core samples, and are free from any bias that might be introduced into the selection of core samples by the testing requirements. Nevertheless, the wireline logs were compared with the results of tests on core, to establish whether different measurements of any particular property arise from the two methods, and to account for any such differences (Nirex 1997f).

Wireline logs of neutron porosity (NPHI), bulk density (RHOB), compressional velocity (VPW) and shallow resistivity (LLS) were used to develop a Wireline Property Log, which was combined with other parameters (the Stoneley Wave Reflection Coefficient and borehole records of Flow Zones and Potential Flowing Features) to produce rock quality and hydrogeological indices. The purpose of the indices was to enable data of interest for rock quality and hydrogeological assessments to be summarised and combined, in order to indicate the principal characteristics of the rock mass within a given volume.

Down-hole variography was used to investigate the vertical spatial variability of rock mass and fluid properties at Sellafield. The results indicated that most of the spatial variability in the Permo-Triassic sedimentary rocks is small scale (2m - 8m) and probably related to small scale sedimentary architecture of the sandstones. The Borrowdale Volcanic Group exhibits spatial variability at short, medium and long length scales.

Acoustic impedance was the key parameter used for extrapolating rock mass properties from boreholes into the three-dimensional rock mass, because it can be derived from wireline logs to give borehole acoustic impedance, and from the inversion of seismic data to give seismic acoustic impedance. Establishing a relationship between borehole acoustic impedance and the rock quality index, the hydrogeological index, and properties such as porosity and permeability, enabled these properties to be extrapolated into three dimensions by way of the seismic acoustic impedance volume derived from the 3D trial seismic survey.

The relationships between acoustic impedance and the rock quality and hydrogeological indices were investigated using fuzzy logic techniques. These seek to identify which category (or categories) of each index could be represented by a particular acoustic impedance value. The method showed promise when used at Sellafield. Direct correlations between measures of rock quality (RMR) and acoustic impedance, porosity and acoustic impedance, and permeability and acoustic impedance, were also investigated. Such correlations established empirical relationships between these properties and acoustic impedance which are valid for the data from Sellafield, though they would not necessarily be applicable in other geological investigations.

The three-dimensional distribution of acoustic impedance was determined from the data obtained by the trial three-dimensional seismic survey in the Potential Repository Zone. Variography was used to determine the spatial variability of acoustic impedance derived from the seismic data set, and geostatistical simulation was undertaken to test whether realisations of three-dimensional acoustic impedance could be generated for the Potential Repository Zone from wireline log data. The simulation takes the spatial variability of the seismic data and applies it to the wireline data, so that wireline-derived values can be extended away from boreholes in three dimensions. As wireline logs have better resolution than seismic reflection data, simulations of acoustic impedance based on wireline data might be expected to contain more detail than displays of seismic acoustic impedance, but with the same characteristics of spatial variability as the latter.

Finally, the empirical relationships between acoustic impedance and Rock Mass Rating (RMR), porosity and permeability were combined with the three-dimensional distribution of acoustic impedance to produce three-dimensional images of the distribution of RMR, porosity and permeability.

It is emphasised that these studies, undertaken in 1996, were preliminary and aimed at investigating methodologies for incorporating geophysical data into estimations of rock mass and fluid properties at scales determined by the resolution of the geophysical measurements and certain aspects require further consideration, for example the correlation between acoustic impedance and the rock quality and hydrogeological indices. Subsequent review of the approach (Evans et al 2002) identified that there were difficulties with the approach used, in particular for low porosity rocks such as the BVG, which potentially magnify errors greatly.

The basic strategy employed by Nirex was to:

- determine rock mass and fluid properties from borehole wireline logs and cores;
- develop single, relative numerical measures (indices) for rock quality and hydrogeological properties from the wireline log data;
- use geostatistical methods to investigate the downhole spatial variability of rock mass and fluid properties;
- derive borehole acoustic impedance from the wireline log data;
- relate borehole acoustic impedance to rock quality and hydrogeological indices using fuzzy logic methods;
- correlate directly between borehole acoustic impedance and measures of rock quality, porosity and permeability;
- invert the trial three-dimensional seismic reflection data to produce a three-

dimensional seismic acoustic impedance dataset;

- use geostatistical methods to determine the spatial variability of seismic acoustic impedance in three dimensions, and then apply that variability to the borehole-derived acoustic impedance dataset to provide an insight into the three-dimensional spatial variability of rock mass properties.

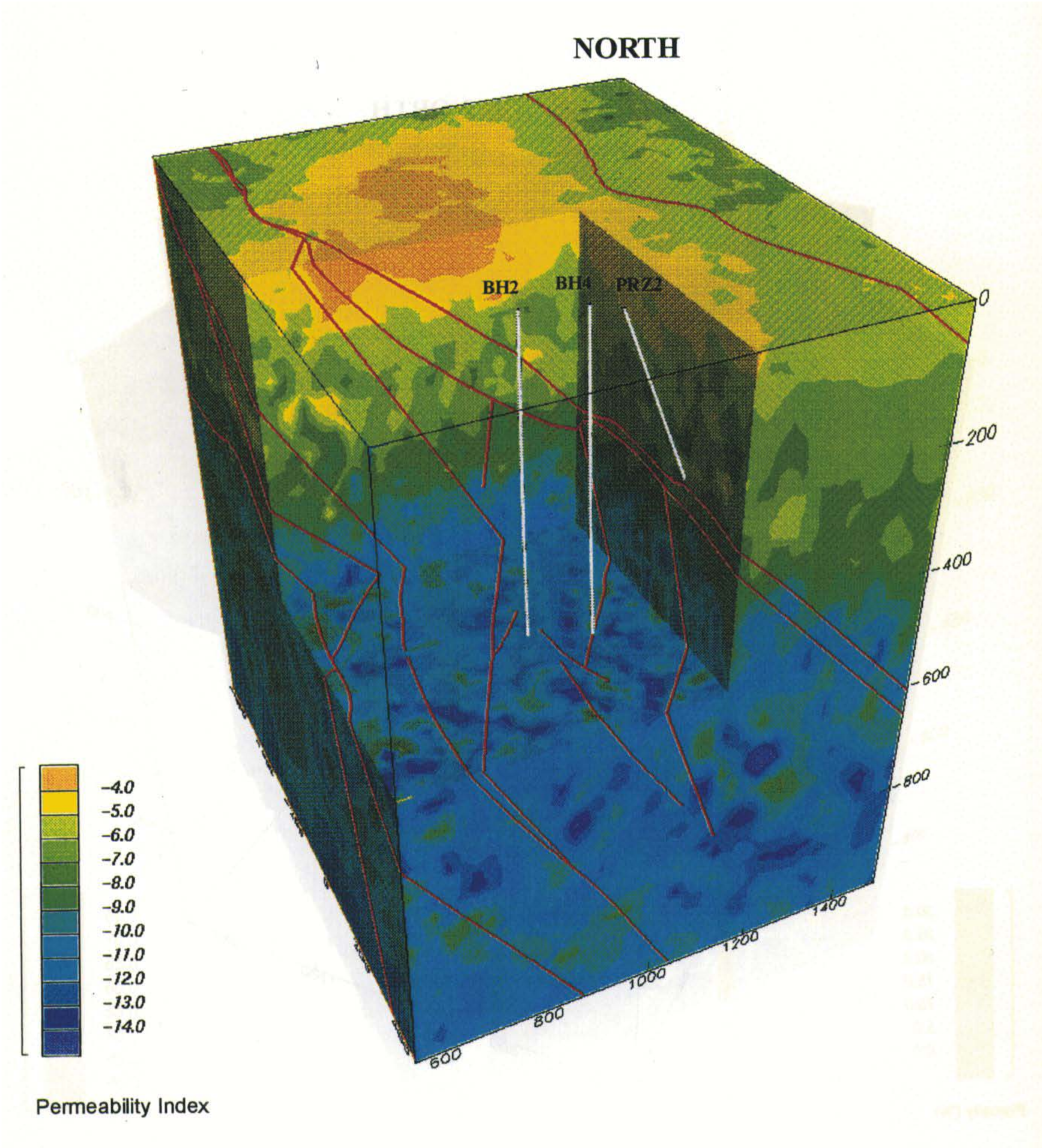



**Figure 4** Rock mass characterisation at Sellafield. Permeability derived from acoustic impedances computed by inversion of 3-D seismic dataset.

### 3.1.9 Interpretation of structural domains from discontinuity data

The interpretation of the large amount of oriented discontinuity (including fractures, faults, bedding etc) data arising from the integration of core and borehole imagery derived datasets (several thousand individual discontinuities per 1000m depth of borehole in the case of the Sellafield boreholes) was helped by the concept of structural domains, or zones (volumes) of consistent character. These structural domains, often closely related to observed lithological units, assisted in the geological correlation between boreholes and the characterisation of the 3D fracture network. This approach is described in Nirex (1997b). The approach adopted for the

Nirex investigations included the development of methodology for the compensation of the censoring effects of, essentially, a one-dimensional sample (the borehole). Further work, which was not undertaken because of the termination of the Sellafield investigations, is needed to confirm the censoring compensation technique developed.

The Structural Atlas provides a synthesis of discontinuity frequency and orientation data for the various rock formations within the Potential Repository Zone area at Sellafield, as measured from core and imagery logs from Nirex deep boreholes 2,4,5, PRZ2, PRZ3, RCF1, RCF2, RCF3, RCM RCM2, and RCM3. The Atlas is based on graphical presentation of the discontinuity and other data against a lithological and structural log and depth scale for each borehole, allowing rapid visual assessment of the data within each borehole and comparison of different boreholes from a number of viewpoints. Structural domain interpretations and statistics, based on analysis of the discontinuity orientation data, are illustrated for the major divisions (Nirex; 1996). Data sources used in the compilation of the atlas are given in Table 1.

| Superset | Entity |
|---|---|
| Borehole logistics | Borehole Path Point (borehole trajectory) |
| | Borehole Geological Log |
| | Formation Top |
| | Fault Intersection |
| | Vein Mineral |
| Borehole Geotechnics Superset | Core Characterisation |
| | Borehole Discontinuity (core log data) |
| | Discontinuity Infill |
| | Discontinuity Mineralogy |
| | Q System |
| | Fracture Index Measurement |
| Geophysics Borehole Superset | Geophysical Log (caliper log) |
| | Geophysical Imaged Discontinuity |
| Borehole Hydrology Superset | Production Log Flow Zone |

**Table 1 Data used in the compilation of the Structural Atlas (Nirex 1996).**

The borehole discontinuity data comprise two primary data-sets, available from core logging and the interpretation of borehole imagery, and a secondary, integrated data-set produced by the use of the imagery data to orientate the core data. Together, these allowed a broad range of small-scale structural features and their spatial variability to be characterised in the context of lithology and structural position. Core data present a range of attributes for those features in the core which fall within the logging definition of discontinuities and the guidelines for recording them extant at the time of logging (GDGG 1994), but no true orientation information was available. Borehole imagery maps electrical/acoustic variations in the borehole wall and planar features passing through the borehole are recognised as a sine wave from which a true orientation can be determined. Interpretation of the imagery tends to select the most prominent features at any location. These represent a variety of discontinuity types in the rock mass (usually joints and other fractures, veins or faults) but may also record features which do not fall within the definition of discontinuities (e.g. bedding or other primary fabric where there is no physical discontinuity).

The Atlas is based on two summary charts for each borehole:

- Frequency and orientation information for the discontinuity data against various other borehole data.

- Strike and dip statistics of imagery and orientated core discontinuity data in the principal, lithologically controlled domains.

A further six, map-based charts allowed comparison of the discontinuity orientation data from each borehole for the lithological domains which can be recognised in most of the Potential Repository Zone area boreholes. The component parts of these plots are briefly described below.

Discontinuity frequency and orientation charts illustrate the discontinuity frequency and orientation data and provide summary data from structural domain interpretations. The latter are founded on analysis of the imagery orientation data carried out initially independently from other borehole data, leading to definition of the imagery orientation domains. This analysis concluded that primary lithology is the principal control on the discontinuity characteristics over long borehole sections, although faults influence the pattern locally. Hence, the lithological domains were defined by dominant lithology to represent the gross character of the data. As the lithostratigraphic units have been defined on a similar basis, they commonly match the lithological domains and the same nomenclature has been used.

Summary orientation data for each lithological domain comprise pole and contoured stereographic plots and a rose diagram of strike of the imagery data and a pole plot of orientated core data on which the main discontinuity types are distinguished by colour. Lithological control over the discontinuity orientation and frequency character is most apparent between the cover sequence (Brockram and St Bees Sandstone) and the Borrowdale Volcanic Group (BVG) but is also seen within the latter dependent upon original lithology, particularly whether the rock was welded or not at the time of deposition.

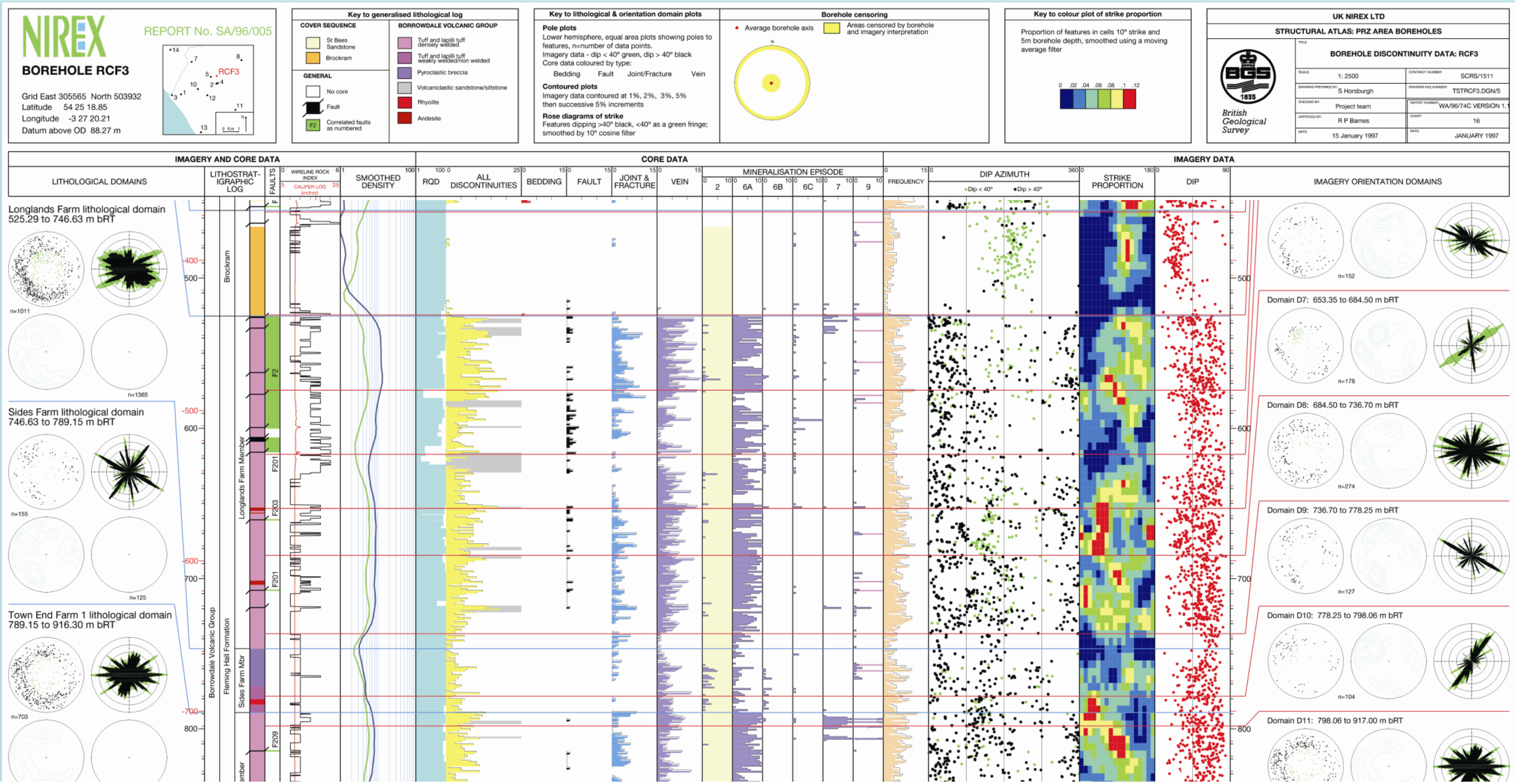


Figure 5 Part of the Structural Atlas summary for RCF3. Note that the upper half of the image is Permo-Triassic and the lower part BVG. Even at the scale of reproduction above differences in fracture density (purple histograms) and orientation (rose diagrams) within the BVG are distinguishable (Nirex 1996).

### 3.1.10 Potentially Flowing Feature Logging

Mineralogical logging of the cores at Sellafield was used to identify individual features (whether discontinuities, faults or zones of enhanced porosity) that showed mineralogical evidence of being connected to the groundwater flow network (see e.g. Nirex 1995b). This involved the systematic visual examination and recording of the mineralisation associated with fractures and other discontinuities in drill-cores from the borehole. Where possible orientations for PFFs were determined using the oriented discontinuity information to provide true orientation (dip and dip direction). In addition to recording mineral assemblages, an attempt was made to assign the mineralisation in individual fractures to one or more of the Mineralisation Episodes (ME), see Table 2 for details. Where possible, the fracture mineralisation observed during core logging was assigned within the ME scheme on the basis of one or more characteristic (and sometimes unique) features of the different MEs established from detailed petrographical investigations of mineralization. A similar, related, scheme was established for digenetic mineralisation.

<table>
<tr><th colspan="2">Mineralisation Episode (ME)</th><th>Principal associated minerals</th><th>Dominant type of mineralisation</th></tr>
<tr><td colspan="2">ME1</td><td>K-feldspar/adularia, ±quartz, ±chlorite, ±albite, ±hematite</td><td>Silicate</td></tr>
<tr><td colspan="2">ME2</td><td><u>Quartz</u>, ±epidote, ±calcite, ±chlorite, ±apatite, ±K-feldspar, ±albite, ±sericite, ±hematite</td><td>Silicate (and carbonate)</td></tr>
<tr><td colspan="2">ME3</td><td><u>Pyrite</u>, ±traces of chalcopyrite, arsenopyrite, marcasite, galena, sphalerite, Bi-Se sulphosalts and quartz</td><td>Sulphide (and silicate)</td></tr>
<tr><td colspan="2">ME4</td><td><u>Anhydrite</u>, Vbarite, ±fluorite, ±hematite, ±quartz, ±siderite (?),±K-feldspar</td><td>Sulphate</td></tr>
<tr><td colspan="2">ME5</td><td>Albite, K-feldspar, <u>kaolinite, illite</u>, ±hematite</td><td>Silicate</td></tr>
<tr><td rowspan="3">ME6</td><td>a</td><td>Early ME6a: ferroan/manganoan carbonate now replaced completely by specular hematite and <u>calcite</u> with abundant inclusions of Fe and Mn oxides.<br>Late ME6a: <u>calcite</u> and hematite</td><td rowspan="3">Carbonate ±sulphate</td></tr>
<tr><td>b</td><td>Dolomite, <u>ferroan dolomite</u>, ankerite, ±siderite, ±quartz, ±anhydrite, ±ferroan calcite</td></tr>
<tr><td>c</td><td><u>Calcite</u> (usually ferroan), ±barite, ±fluorite, ±hematite, ±sphalerite, ±galena</td></tr>
<tr><td colspan="2">ME7</td><td><u>Illitic clay</u> and <u>hematite</u></td><td>Silicate and oxide</td></tr>
<tr><td colspan="2">ME8</td><td><u>Mn- and Fe-oxidxes/oxyhydroxides</u></td><td>Oxide</td></tr>
<tr><td colspan="2">ME9</td><td>Calcite, ±pyrite, anhydrite, ±gypsum</td><td>Carbonate ±sulphate ±sulphide</td></tr>
</table>

**Table 2** Fracture mineralisation chronology, principal associated minerals and mineralisation types in Sellafield boreholes.

This technique identified tens to low hundreds of potentially flowing features (PFF), which are characterised by the presence of ME8 and ME9 mineralisation, in a typical borehole. These features were often clustered around those identified by production logging and flow zones are often associated with major structures, such as faults. The integration of PFF logging with borehole imagery provides an integrated data set that includes attributes determined from an examination of the core sample, such as, mineralogy, infill, vuggy aperture etc, with attributes determined from the wireline logs, such as orientation, aperture, flow etc. (Milodowski et al, 1998, Nirex, 1998a 1998b). The resulting oriented PFF data set was a key element in the process of understanding the groundwater flow regime.

The ability to undertake this detailed logging approach was the result of the understanding of the phases of mineralisation and their relative ages derived from the detailed examination of fracture mineralogy in drill cores under the core characterisation programme where a wide range of methods, including optical petrology, scanning electron microscopy, cathodoluminescence, fluid inclusion studies, were applied (see Shaw 1994 for details).

### 3.1.11 Tectonics

#### 3.1.11.1 Seismic Hazard

Using the Seismic Hazard Working Party (SHWP), a multi-disciplinary group of specialists who were individually retained by Nuclear Electric plc and who were responsible for all aspects of seismic hazard assessment, for Nuclear Electric sites or projects, Nirex undertook a study of seismic hazard in the Sellafield area. Individual members of the SHWP had topic responsibility for special subject matter for historical (pre-instrumentation) and macroseismic (felt) earthquakes, and instrumental earthquakes. Material produced by these topic specialists was reviewed by at least one member of the SHWP. Major decisions, such as the area of investigation for the seismological database, or earthquake catalogue completeness thresholds were referred to Plenary Meetings of the SHWP for endorsement. Decisions made at Plenary Meetings' where all the core members of the SHWP were present, based on the open elicitation of expert judgment, whether or not they had been involved in the data-gathering, the topic specialists, and such other members of the SHWP whose presence was required by the nature of the material to be discussed or by the nature of the decisions to be made. By this means, all the relevant expertise available within the SHWP was present, including those who had been jointly and severally responsible for the introduction into the project of the various elements of the database and, therefore, had detailed knowledge extending across its entire range, including the extent of the uncertainties (Nirex 1995f).

The SHWP catalogued seismological evidence for earthquake activity in the area around Sellafield. This evidence is of two kinds, macroseismic and instrumental, the former extracted largely from historical documentary sources extending back over more than thirteen centuries. Instrumental data are far more numerous but come mainly from only the last two decades. The catalogue (1995) listed 308 earthquakes of which 68 were interpreted solely from macroseismic information, 220 from instrumental recordings, and 10 have complementary information of both kinds. The highest magnitude earthquake recorded in the Sellafield area (to 1995) was the 4.7$M_{SA}$ 1786 Whitehaven earthquake, while the highest Intensity (VII-VIII) is attributed to the 1865 Rampside event, which has an assessed magnitude of 3.0$M_{SA}$.

#### 3.1.11.2 In-Situ Stress

In-situ stress determination in large volumes of rock is valuable information for understanding the ongoing geological and geophysical processes in the earth's crust at the present time. Also in-situ stress, or the state of stress in rocks, has a central role in design of underground excavations.

In the Sellafield investigations, many aspects of geotechnical modelling required knowledge of the in-situ stresses in order to set constraints on boundary conditions and limit the range of plausible results both in prediction and during subsequent evaluation. An estimate of the stress field was also an input to modelling to evaluate the performance of the repository during the pre- and post-closure periods.

A study of the in-situ stress at Sellafield was undertaken by a multi-contractor team as part of the JIT work which collated, analysed and interpreted all the available data from boreholes drilled in the Sellafield area. The in-situ stress orientations and magnitudes were estimated using independent methods. The primary orientation results were estimated from processing 72 sets of induced hydraulic fracturing and 'breakout' images obtained from ten Sellafield boreholes by geophysical logging. The results were compared with those derived from overcoring stress measurements in Borehole No. l0B and seismic fault plane solutions. The trends of the in-situ principal stress magnitudes with depth were determined or computed from in-situ density and hydrofracture stress measurement data from five boreholes and the overcore stress measurement results (Nirex 1997i).

The work was split into two major components:

- The evaluation and presentation of the orientations of the maximum principal stress;
- The analysis and estimation of the magnitudes of the three principal stresses.

The results were compared with two other indicators of the local stress field. Firstly, the fault plane solutions of seismic events in the vicinity of the site and, secondly, the direction of the major faults in the proposed RCF area. The comparison has shown that all of the results were consistent with each other. It was concluded that the maximum horizontal stress orientation data could be averaged as a single population with a mean orientation of 339° ±3.5° as 95% confidence (with a range from about 298° to 010°) (Nirex 1997i).

### 3.1.12 RCF Predictions

In advance of the proposed sinking of the Rock Characterisation Facility (RCF) shafts at Sellafield a series of detailed prediction activities were commenced to predict various aspects of the geology that would be encountered during shaft sinking. Only the gross (overall) predictions were completed, the cancellation of the RCF in 1997 meant that the detailed sector predictions for different parts of the shafts, based on the different geological units, were not undertaken. The gross predictions were published as a six volume report (Nirex 1997k) with Volume 1 being the predictions and the other volumes presenting the results of addition studies to develop the then current understanding of specific issues. The gross geological predictions were made for both the RCF North and South Shafts.

Assessments of the safety of a potential repository at the site published in 1995 (Nirex 1995c) had helped to identify some remaining uncertainties that needed to be addressed in the RCF before Nirex could take a decision on whether or not to propose a repository at the site. These uncertainties relate to aspects of:

- groundwater flow and radionuclide transport;
- natural and induced changes to the geological barrier;
- design and construction of the repository.

Some of these uncertainties would have been addressed by testing models related to the geology, hydrogeology and geotechnical behaviour of the site during the construction of the RCF. The geological models were a deterministic interpretation of the geological, lithostratigraphic and structural framework and described the spatial variability of rock mass properties, using both deterministic and probabilistic approaches. These geological models underpinned the hydrogeological and geotechnical models.

The models that were developed would have been tested by preparing predictions of conditions to be encountered in the RCF, particularly within the shafts during Phase 1A of construction, and by making the measurements necessary to compare actual observations with the predictions. The models acknowledged that conditions would not have been uniform in the RCF because, for example, the shafts would have penetrated different rock types (sandstone, sedimentary breccia and volcanic rocks). In addition, particular geological and hydrogeological features would have been encountered in specific parts of the shafts, for example: significant faults, Fault F3 in the sandstones and Fault F2 in the volcanic rocks; and the Saline Transition Zone (STZ) over which groundwater salinity changes from fresh/brackish to saline. In order to design the measurements to test the models, Phase 1A of the planned RCF development was sub-divided into sectors within which different geological, hydrogeological and geotechnical conditions were anticipated and, therefore, within which different combinations of measurements would have been required to test the models.

The gross predictions comprised:

- The geological and hydrogeological setting;
- Predictions of deterministic geology at the RCF Shaft Scale, incorporating local-scale detail of Fault F2 and Fault F3;
- Predictions made from the Structural Domains Model;
- Predictions made from the Sedimentary Architecture Model;
- Predictions made from the Rock Mass Properties Model;
- Predictions made from the Mineralisation Episodes Model.

Volumes 2 to 6 of the predictions report (Nirex 1997k) described additional studies carried out in support of the development of the predictions made in Volume 1, as follows:

- Volume 2 - Characterisation of an Alteration Zone within the Borrowdale Volcanic Group;
- Volume 3 - Characterisation of the Longlands Farm Member Mesobreccia within the Borrowdale Volcanic Group;
- Volume 4 - Evaluation of Structural Dip within the Borrowdale Volcanic Group;
- Volume 5 - Lithostratigraphical Correlation of the Borrowdale Volcanic Group in the Potential Repository Zone;
- Volume 6 - Structural Domains Predictions for the Sellafield Rock Characterisation Facility.

The report was part of a series that comprised:

- Hydrochemical model development: Gross RCF predictions;
- Hydrogeological model development: RCF shaft model predictions;
- Hydrogeological model development: Gross RCF predictions;
- Geotechnical model development: Gross elastic predictions;
- Geotechnical model development: Gross discontinuum predictions.

### 3.1.13 Summary of approaches used and their application

Table 3 summarises the methods used in the Sellafield evaluation programme and what they were used for.

The Nirex Sellafield investigations used a wide variety of approaches, many of them ‘borrowed’ from the hydrocarbon industry, to undertake the geological interpretation and modelling of the area being investigated at that time. The trial 3D seismic survey was one of the first undertaken on-shore and it provided a large amount of data to refine the geological model of the PRZ area, in particular down to the top of basement (seismic imaging in the basement was not as good as in the cover rocks). As well as structural geological information the data were integrated with core and wireline derived information and processed to derive rock quality and hydrogeological indices.

The integration of core discontinuity data with information derived from borehole imaging and with dynamic features (e.g. the PFF logging at Sellafield) was a key process in understanding the site’s flow regime, not only the current regime but also palaeoflow regimes.

| *Information requirement* | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|
| **Mapping (topographical, geomorphological and geological)** | Detailed geological mapping | Determine the main features of the geological environment. Used for conceptual model of geology and development of 3D digital geological models. |
| **Basement rocks; nature, distribution and properties** | Deep boreholes; core logging | Detailed understanding of rock units and their inter-relationships.<br>Volcanic and depositional processes (in the BVG) |
| | 2D seismic surveys | Initial local onshore reconnaissance:<br>Infill to initial local reconnaissance:<br>Regional survey;<br>Offshore regional survey;<br>Transition-zone - tie lines between onshore and offshore regional surveys;<br>Detail around proposed repository site and tie-lines to regional surveys. |
| | 3-D seismic survey | To provide detailed information around 3-D volume of proposed RCF. |
| **Sedimentary rocks; nature, distribution and properties** | Airborne Geophysics | To provide data to help identify thickness of sedimentary cover |
| | Surface based gravity | To provide data to help identify thickness of sedimentary cover. |
| | Facies mapping | Conceptualisation of depositional environments |
| | CSAMT | Depth to saline interface |
| | Deep boreholes; core logging | Detailed understanding of rock units and their inter-relationships.<br>Sedimentary architecture<br>Volcanic and depositional processes (in the BVG) |
| | 2D seismic survey | Initial local onshore reconnaissance:<br>Infill to initial local reconnaissance:<br>Regional survey;<br>Offshore regional survey;<br>Transition-zone - tie lines between onshore and offshore regional surveys;<br>Detail around proposed repository site and tie-lines to regional surveys. |
| **Superficial "drift" deposits; nature, distribution and properties** | High resolution 2D seismic survey | To investigate possible structures affecting Quaternary succession |
| | Shallow boreholes | Characterization of the Quaternary glacial sediments and for drill site civil engineering purposes. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Geological structure** | **Identification of fault structures** | Airborne Geophysics | To provide data to help identify/major fault structures |
| | | Surface based gravity | To provide data to help identify/mMajor fault structures |
| | | Deep boreholes<br>-core logging | Fault and fracture logs to understand fault and fracture patterns |
| | | Fracture mapping | 3D distribution of fractures etc. |
| | | Mine Plan studies | Development of understanding of faulting in the area |
| | | Remote sensing | Large scale lineaments (may/may not be related to larger fault structures |
| | | High resolution 2D seismic survey | Used to identify potential faulting and deformation structures |
| **Mineral Deposits** | | Mineralogical/PFF logging | Detailed examination of fracture (and diagenetic) mineralisation to understand palaeo and current fluid flow. |
| **Tectonics** | | High resolution 2D seismic survey | Test line over possible neotectonic features imaged on earlier Vibroseis data;<br>Additional lines over possible neotectonic features |
| **Spatial heterogeneity** | | Airborne Geophysics | To provide data to help identify:<br>- possible intrusions<br>possible Skiddaw Slate/BVG distribution in basement |
| | | Surface based gravity | To provide data to help identify:<br>- possible intrusions<br>- possible Skiddaw Slate/BVG distribution in basement |

**Table 3** Inventory of methods used by Nirex in their Sellafield investigations 1988-1997 and main purposes that the data were used for.

## 3.2 THE SKB FORSMARK AND LAXEMAR EXAMPLES

Radioactive waste from the Swedish nuclear power plants is managed by the Swedish Nuclear Fuel and Waste Management Co (Svensk Kärnbränslehantering AB - SKB). SKB's early work identified that the Swedish crystalline basement rock was, in general, suitable for the geological disposal of radioactive waste. After more than two decades of consultation and preliminary site investigations in eight municipalities, SKB then undertook detailed site characterisation at two different locations, Laxemar-Simpevarp and Forsmark in order to identify a suitable location for a geological repository of spent nuclear fuel. SKB have recently (March 2011) submitted permit applications for the construction of a repository at Forsmark.

SKB started site investigations at both sites in 2002. The site investigations have been conducted in campaigns, punctuated by data freezes – see Table 4 and Table 5 (Page 15 of TR 09-01 (SKB 2009) provides details). These data freezes have been taken as definite and new or late information that missed the cut was held over to the next phase. After each data freeze, the site data have been analysed and modelling has been carried out with the overall purpose to develop a site descriptive model (SDM). The site descriptive model is then used to inform the design the underground facility and to develop a repository layout adapted to the site. It is also essential for safety assessment because the SDM is the only source for site-specific input. Another important use of the site descriptive model is in the environmental impact assessment. The SDM is an integrated model of geology, thermal properties, rock mechanics, hydrogeology, hydrogeochemistry, bedrock transport properties and a description of the surface system.

The site descriptive model (SDM) compiled for Forsmark presents an integrated understanding at the completion of the surface-based investigations, which were conducted during the period 2002 to 2008. This is detailed in TR08-05 (SKB 2008). The site descriptive model (SDM) compiled for Laxemar, presents an integrated understanding of the Laxemar-Simpevarp area (with special emphasis on the Laxemar sub-area) at the completion of the surface-based investigations, which were conducted during the period 2002 to 2007. This is detailed in TR09-01 (SKB 2009). These two assessments were completed in parallel prior to the decision on which site to take forward for an application for the development of a repository. The approaches adopted at both sites are similar and this section focuses on the work undertaken during the Forsmark investigations supplemented with information from the Laxemar investigations where appropriate.

| Model | Data freeze | Reference |
|---|---|---|
| Forsmark SDM Version 0 | 2002 | SKB R-02-32<br>(SKB; 2002a) |
| Forsmark SDM Version 1.1 | | SKB R-04-15<br>(SKB; 2004b) |
| Forsmark SDM Version 1.2 | 31 July 2004 | SKB R-05-18<br>(SKB; 2005b) |
| Forsmark Model 2.1 | 29 July 2005 | SKB R-05-17<br>(SKB; 2005c) |
| Forsmark SDM-Site | 30 September 2006 (Forsmark 2.2)<br>30 March 2007 (Forsmark 2.3) | SKB TR-8-05<br>(SKB; 2008) |

**Table 4** Forsmark site investigations with data freeze dates (SDM – Site Description Model)

| Model | Data freeze | Reference |
|---|---|---|
| Version Simpevarp 1.1 | 1 July 2003 | SKB 2004 R-04-25<br>(SKB; 2004a) |
| Version Simpevarp 1.2 | 1 April 2004 | SKB 2005 R-05-08<br>(SKB; 2005a) |
| Version Laxemar 1.2 | 1 November 2004 | SKB 2006 R-06-10<br>(SKB; 2006a) |
| Stage Laxemar 2.1 | 30 June 2005 | SKB 2006 R-06-110<br>(SKB; 2006b) |
| Version SDM-Site Laxemar | 31 December 2006 (Laxemar 2.2)<br>31 August 2007 (Laxemar 2.3) | SKB 09-01<br>(SKB; 2009) |

**Table 5** Laxemar-Simpevarp site investigations with data freeze dates

Only data in the SKB SICADA database at the time of the data freeze was available for use during the subsequent integration and modelling activities.

The investigations focussed on providing improved insight in brittle structures through geophysical measurements, lineament interpretation, characterisation of the bedrock in dug trenches and studies of the character and kinematics of deformation zones, the latter both at the surface and in boreholes. A dedicated effort was also made to identify and characterise local minor deformation zones, both on the surface and in boreholes. Other investigations, including geochronological studies, have also been completed.

### 3.2.1 Mapping (topographical, geomorphological and geological)

The main objective of the mapping was to develop an overall view of the geology of the two target areas, particularly with regard to:

- Superficial deposits; and
- The underlying Fennoscandian Shield

Geological mapping was initially based on the information available for the Swedish Geological Survey (SGU) and subsequently supplemented by additional surface based mapping. The latter included mapping of exposures/trenches for fractures related information in particular. The Quaternary cover deposits, though largely relatively thin, were mapped both on and off shore and geological information on these deposits was supplemented by information from shallow boreholes. Landform feature mapping was used to assist the elucidation of the most recent glacial history of the area.

Mapping of rock units, ductile structures and fractures at the surface during the initial site investigation up to data freeze 1.2, subsequent geological investigations in the Forsmark area have focussed on adding new insight on brittle structures (faults) at depth by interpretation of reflection seismic measurements, refraction seismic measurements and lineament characterisation. Other investigations, including complementary detailed mapping of fractures in parts of the bedrock that is not transected by lineaments close to drill site 7 and transient electromagnetic soundings, have also been completed.

Three approaches were used for lineament characterisation, which is important for the identification of steeply dipping fracture zones. Firstly, high-resolution ground magnetic measurements were carried out within the Forsmark investigation site to provide a detailed ground magnetic representation of the bedrock. The second method was to excavate trenches across previously identified lineaments. In these trenches the bedrock surface was carefully studied and the rock type and fracture distribution mapped in detail. Ground geophysical measurements (detailed magnetometry, continuous vertical electric sounding and ground penetrating radar) were also performed on the exposed rock surface to supplement the geological mapping. The third method used drilling to infer the continuation of lineaments as geological anomalies. A similar area was exposed to carry out complementary detailed mapping of fractures in the bedrock of an area not transected by lineaments. The same detailed geophysical measurements as those completed along the excavations across lineaments were also performed at this site. This allowed comparison of the fracture patterns present in rock affected by lineaments and that not so affected.

In addition to the data collected during the site investigation programme at Forsmark, older geological and geophysical data from the Forsmark nuclear power plant and SFR have been used in the geological modelling work. These data are only partly stored in the SICADA database, and they are not necessarily of the same quality as the data generated by the site investigation programme. Specific examples include seismic refraction data, borehole data from DBT-1 and DBT-2, borehole and tunnel data across the Singö deformation zone and photographs of sub-horizontal sheet joints along the channel that provides cooling water to the nuclear power plant.

The investigations of the surface system carried out between data freezes 1.2 and 2.3 involved the following disciplines:

- Bedrock geology and ground geophysics comprising
    - Reflection seismic measurements;
    - Refraction seismic measurements;
    - Lineament characterisation;
    - Complementary detailed mapping of fractures in the bedrock not transected by lineaments;
    - Transient electromagnetic soundings;
- Quaternary geology and ground geophysics comprising:
    - Mapping of Quaternary;
    - Stratigraphic investigations;
- Surface ecology (not considered further here).

### 3.2.2 Basement rocks - nature, distribution and properties

Apart from gaining information on the limited superficial deposits present in the area the SKB investigations at Forsmark were aimed at developing a detailed understanding of the Fennoscandian Shield rocks underlying the area. Because the Forsmark area consists of crystalline bedrock that has been affected by both ductile and brittle deformation the main focus of the site investigations has been to understand this deformation (see section 3.2.4 below).

### 3.2.3 Superficial (drift) deposits - nature, distribution and properties

Investigations of on-shore Quaternary deposits were initiated in 2002 and continued for the next two years. This involved the 'traditional' geological mapping approaches and the interpretation of this data in conjunction with landform characterisation. After data freeze 1.2, an effort was directed towards the completion of the Quaternary geological map in the shallow offshore area and towards stratigraphic studies.

The mapping of Quaternary deposits was completed with investigations of the bottom sediments in shallow bays offshore the coast at Forsmark. The results fill the gap between the previously produced map of Quaternary deposits on land and the marine geological map. The latter covers areas with a water depth exceeding 3 m. The mapping was performed by coring and probing from the sea ice and from a small boat and the resulting map includes 140 stratigraphic descriptions.

On-shore stratigraphic investigations in two machine-excavated trenches were carried out, supplemented with information from samples from cores, most of them located inside the candidate area, in order to gain additional information on the Quaternary stratigraphy. Lithostratigraphic sampling, sample analysis and descriptions of Quaternary deposits were conducted on cores from three different types of wetlands and from some locally elevated sites within the Forsmark regional model area. The information from the sampling and the landform characterisation was used to interpret the (recent) Quaternary geology of the Forsmark area.

### 3.2.4 Geological structure

The ductile deformation in the Forsmark area has resulted in large-scale, ductile high-strain belts and more discrete high-strain zones. Tectonic lenses, in which the bedrock is less affected by ductile deformation, are enclosed between these ductile high strain belts. The candidate area is located in the north-westernmost part of one of these tectonic lenses. The later brittle deformation has given rise to reactivation of the ductile zones in the colder, brittle regime and the formation of new fracture zones with variable size.

Orientations of geological structures (e.g. fractures, rock contacts, foliations) in boreholes for both Laxemar and Forsmark (SKB 2008) were identified during borehole logging with the Borehole Imaging Processing System (BIPS). This is a downhole optical imaging system which, together with inspection of the drill core or, for percussion boreholes, drill cuttings, was used to support the so-called Boremap mapping. During the processing of the borehole imagery, the orientation of identified geological structures was calculated on the basis of borehole geometry and measured geometry relative to the borehole axis.

The results from standard geological and geophysical borehole investigations and single-hole interpretations, which are regarded as 1D models, are available. However, the only investigations carried out in the shallow boreholes KFM90A–E were BIPS-logging, drill-core mapping and deviation measurements. More information on these standard investigations can be found in SKB 2008.

Vertical seismic profiling measurements were undertaken in the two deep, almost vertical telescopic boreholes KFM01A and KFM02A in order to improve the resolution in the identification of seismic reflectors and to provide some constraints on the extension of geological structures. The surveys were conducted to a borehole length of 775 m in each borehole. Major seismic features were identified to depths exceeding 1.5 Km and to a lateral distance of 2–3 Km from the borehole collars. Measurements of ground currents generated by the Fennoskan high-voltage cable were performed in boreholes KFM04A, 07A and 08A. Ground self-potential measurements were also conducted between drill sites 4 and 1.

At Laxemar detailed fracture mapping was conducted at two surface excavations (drill sites for KLX09 and KLX11A/KLX20A) and along a total of 600 m dug/cleared trenches (divided into 10 segments) located in two different rock domains and with variable orientations. The mapping of fractures along these trenches has been made in a 1 m wide corridor with a truncation length of 1 m. The trenches have also been subject to high resolution photography at 3 m altitude enabling rectified photo mosaics to be made along the studied trenches. The structural data from these trenches serve as complements to the information collected from the otherwise essentially vertical/subvertical boreholes.

A number of investigations have been conducted to serve as a basis for lineament characterisation and targeted investigations of minor local deformation zones (MDZ). These include high resolution ground magnetic measurements and resistivity profiling and soundings. These measurements originally only covered the northern and central parts of Laxemar, excluding areas south of the valley hosting the Laxemarån river and the interpreted deformation zone ZSMNW042A.

In addition to this information, low altitude aerial photographs and measurements by airborne laser scanning technique (LIDAR) were used to obtain a detailed high-resolution digital elevation model (DEM) of Laxemar. Refraction seismic measurements have also been carried out along profiles that cover a large part of the Laxemar sub-area, targeting primarily lineaments related to potential deformation zones. The geological and geophysical investigations were completed by investigating selected lineaments by drilling.

A major study of predominantly brittle structures has been performed in three stages with the purpose of documenting the detailed character and kinematics of brittle deformation zones identified in the geological single-hole interpretation. Structural data were obtained from 19 cored boreholes covering some 65 deformation zones. In addition, structural data have also been obtained from outcrops in the Laxemar-Simpevarp area.

### 3.2.5 Geological Interpretation and Modelling

The objective of the interpretation and modelling was to develop a site descriptive model (SDM) for both Forsmark and Laxemar at both a 'regional' and 'local' volume scale giving a difference in resolution. Thus the regional model captures main features to a depth of 2100 m below sea-level whereas the local model focuses on the target area of the potential repository.

Data available at the start of the site investigations in 2002 was included in a preliminary model, version 0. After data freeze 1.2 a revised model, version 1.2 (SKB, 2005c), was constructed using the data acquired from the start of the site investigations at the beginning of 2002 to July 31st 2004. The data for this model was acquired in three main categories of investigations:

- Geoscientific and ecological investigations of the surface system, including the compilation of bedrock and Quaternary cover geological maps;
- Borehole investigations. They comprised:
    - Drilling of long, so-called telescopic boreholes (the upper c. 100 metres are percussion drilled whereas the remainder is core drilled), conventionally drilled cored boreholes, percussion boreholes and shallow boreholes through Quaternary deposits;
    - Measurements carried out during drilling, logging of drill cores and drill cuttings during and after drilling, and down-hole logging;
    - Sampling of intact rock material for several types of laboratory investigations;
- Monitoring of geoscientific and ecological parameters. Monitoring has expanded successively during the entire site investigation period. The previous monitoring activities as well as the planned future monitoring after completion of the site investigations are presented in (SKB 2007).

The extent and character of data acquisition up to data freeze 1.2 are described in detail in (SKB 2005d) and supporting documentation.

The structure investigation was subsequently applied to the site investigations prior to each of the succeeding data freezes.

The site investigations associated with data collection between data freezes 1.2 and 2.3 comprised the three main categories of investigations noted above. Following each of these data freezes, analytical and modelling work was completed. Major modelling activities were based on the information from data freeze 2.2, while new information at data freeze 2.3 and also, if possible, late data (data not available until after the data freeze) were used primarily for model verification purposes and complementary analytical work. Several of the field investigations had long execution periods which sometimes overlapped the data freezes. Data from these investigations feed into succeeding freezes.

The general framework for the site investigation programme after data freeze 1.2 published in 2005 (SKB, 2005d). The detailed strategy regarding, for example, location of new boreholes, selection of borehole sections for groundwater sampling, layout design for ground geophysical measurements etc was largely established by an iterative process, where previous results guided subsequent decisions concerning continued investigations. This process involved a close integration between the site investigation and site modelling working teams.

### 3.2.6 Modelling

Prior to the final site descriptive model, known as SDM-Site, which was used in the safety assessment SR-Site, three complete and integrated site descriptive models for Forsmark have been produced. These were:

**Version 0**

The first model developed from the information available at the start of the surface-based site investigation programme. This information was mainly 2D in nature. It was also general and regional, rather than just detailed, site-specific in character.

Two model versions, version 1.1 and version 1.2, were developed based on data from the initial site investigation stage.

**Version 1.1**

This modelling was primarily a training exercise. It was built on an extensive set of data from the surface but limited borehole data (one c. 1,000 m deep cored borehole (and eight c. 150–200 m deep percussion-drilled boreholes).

**Version 1.2**

The modelling undertaken for version 1.2 generally confirmed the version 1.1 model. It had considerably more sub-surface data but required only minor modifications to the descriptions of rock units, including the character of the ductile deformation in the bedrock (rock domain model). Enhanced confidence in rock strength and thermal properties was also achieved, because the analyses and modelling confirmed the ranges obtained in version 1.1. The main remaining uncertainties concerned the impact of subordinate rock types on thermal and strength properties of the rock in the target volume. Stress data and the rock stress modelling confirmed that rock stresses at Forsmark are relatively high compared with typical sites in the central part of Sweden, and that the maximum horizontal stress is aligned approximately NW-SE, i.e. parallel to the overall direction of the tectonic lens and the adjacent steeply dipping regional deformation zones. The existence of deformation zones was confirmed by the analyses of new data for model version 1.2 and new zones were identified in the deformation zone model, in particular a number of gently dipping zones in the south-eastern part of the candidate area. The sensitivity of uncertainties in the geometry of deformation zones and in the hydrogeological properties of these zones were explored by the hydrogeological modelling work. This suggested that the flow in the target volume is mainly local and that the heterogeneity in hydraulic properties within the candidate volume has a significant effect on the local flow distribution. However, these simulations did not consider the existence of highly-transmissive and sub-horizontal, well-connected structures in the uppermost part of the bedrock, which is suggested by hydraulic data from the site. Division of the bedrock into hydraulic domains was carried out during version 1.2 modelling and this approach provided an important feedback to the geological modelling team. An integrated description of the surface system was provided for the first time in this model including Quaternary cover thickness, shallow groundwater and surface water characteristics, as well as terrestrial, limnic and ecosystem models for the drainage area around Lake Bolundsfjärden.

**Stage 2.1**

No integrated site description was compiled as a result of modelling stage 2.1 but updated versions of the geological models for rock domains and deformation zones were developed, and, for the first time, at local scale with a higher resolution.

**SDM-Site**

The boundaries of the stage 2.1 local model volume have been maintained for the final site description, SDM-Site. Compared with model version 1.2, two new, minor rock domains were added in the local model volume, whereas the regional rock domain model strongly resembled the previous versions. Furthermore, the regional model for deformation zones had several similarities to the earlier version, but there were significant changes especially in the length of the gently dipping zones. Particularly, on the basis of the observed three-dimensional spatial variability of open fractures and an inferred relationship between the occurrence of gently dipping fracture zones and the *in situ* stress magnitudes in the bedrock, a conceptual model for division of the rock in the target volume into fracture domains was developed.

### 3.2.7 Model volumes and model areas

The site descriptive modelling is performed using two different scales of model volume, referred to as the 'regional' and 'local' model volumes. The local model is required to cover the volume within which the repository is expected to be constructed, including access routes and the immediate environs. The description of the local model volume is detailed enough for the needs of repository engineering and safety assessment. In addition to the local model, a description is also required for a much larger volume, the regional model volume, so that the local model can be placed in the larger context and to allow for sensitivity analyses of, mainly, hydrogeological boundary conditions.

The difference between the regional and local model volumes is their resolution, which has been chosen to balance the effort required for constructing the models with the needs of downstream users of the models.

### 3.2.7.1 Regional model area and volume

This model area and the corresponding volume were selected so that it:

- Includes the candidate area but is not prohibitively large (surface area of 165 $Km^2$).
- Captures relevant portions of the steeply dipping regional deformation zones, which strike in a north-westerly direction and surround the candidate area. Any expansions of the regional model area to the north-west or south-east would not provide any significant changes in the regional geological understanding. With these considerations in mind, the size of the regional model area is sufficient for the needs of geological modelling. It should be noted that the geological evolution is assessed in the context of a much larger area than the regional model area.
- Adequately covers the variations in rock type in the candidate area and its immediate surroundings.
- Captures the main hydrogeological features of the region, as the boundaries perpendicular to the shoreline are judged to be sufficiently far away from each other that they do not influence the groundwater flow in the candidate area. The boundary to the south-west lies on the south-western side of a local topographic divide, and the boundary to the north-east lies north-east of a major bathymetric break in Öregrundsgrepen. Sensitivity analyses undertaken in version 1.2 of the site descriptive modelling addressed the proper locations of the boundaries in the regional hydrogeological model and the results confirm that the selected regional volume is also appropriate from a hydrogeological point of view.
- Extends to a depth of 2,100 m below sea-level. This is considered to provide a reasonable vertical extent for description and is the maximum depth down to which any meaningful extrapolations of deformation zones could be made. To represent this depth in SKB rock visualisation system, the size of the vertical dimension is set to 2,200 m because the upper boundary is set to +100 m above mean sea level.

### 3.2.7.2 Local model area and volume

The local model area (and corresponding volume) includes the target area selected for a potential repository, where site investigations during the complete site investigation phase were largely focussed. The area modelled during stage 2 is slightly smaller than that undertaken during stage 1 but the boundaries of the former are within those of the latter. This model area and the corresponding volume were selected so that:

- Both to the north-east and south-west, it includes the boundaries to more inhomogeneous and banded bedrock outside the candidate area;
- It includes key rock boundaries within and immediately adjacent to the candidate area which help to define the structural framework within the tectonic lens;
- The north-western and south-eastern model boundaries are located well outside the outer borders of the repository area defined by the repository layout. Furthermore, the north-western boundary is positioned so that the parts of the tectonic lens below the current reactor site as well as potential access ramps from the SFR peninsula are included in the model;

- The surface area is c. 12 $Km^2$;
- A depth of 1,100 m beneath sea level; permitting the inclusion of all information from the existing deep boreholes at the site. To represent this depth in SKB rock visualisation system, the size of the vertical dimension is set to 1,200 m because the upper boundary is set to +100 m above mean sea level;
- An important aspect is the rationale for the choice of volume. Each model has a minimum size of modelled objects to ensure a homogeneous resolution of interpretation throughout the entire model, corner to corner. It is not trivial to compromise between volume size, resolution and efforts to maintain the models. Nested models are an option to resolve the issue.

### 3.2.8 Mineral deposits

No mineral deposits are reported within the area of the Forsmark or Laxemar sites.

### 3.2.9 Spatial heterogeneity

The objective of this work was to establish the variations in heterogeneity in geology which will impact on the development of the SDM.

The 3D survey data were analysed and interpreted by Schmelzbach et al. (2004), who were able to map the 3D geometry of a prominent high amplitude event thought to represent a mafic lense in the intrusive complex. They concluded that the 3D data had significant potential benefits over sparse 2D surveys in crystalline basement terrains.

SKB adopted a similar approach to the structural domains approach used by Nirex noted above (see section 3.1.9). SKB not only subdivided the rock mass into fracture domains, which equate to the Nirex structural, but also into rock domains, hydraulic rock domains (HRD), hydraulic conductor domains (HCD). As with the Nirex structural domains the boundaries of these domains and the different rock units do not necessarily coincide but they often have common boundaries with the deformation zones which generally equal HCD (SKB 2007).

### 3.2.10 Visualization

Visualisation aims to assist in the interpretation of the geological environment by the construction of 3D structural geological models.

The SKB Rock Visualization System (RVS) has been developed by SKB for use in visualizing geological and engineering data (Curtis et al; 2005). It aims to assist in the interpretation of the geological environment by the construction of 3D structural geological models. These models will supply a framework for the creation of integrated models covering all science areas, ultimately leading to the selection and design of the final repository system.

RVS has been under development since 1994 and is based on MicroStation V8.5© and MS/Access 2000©.

RVS has been developed for interpreting data collected during the Swedish radioactive waste disposal programme, including data from the Äspö Hard Rock Laboratory and from the two site investigation programmes. Its focus is on the construction of structural geological models based on borehole and various forms of surface mapping data in crystalline rocks. The system has been integrated with SKB's geological database, SICADA. Models created in RVS can be published or otherwise distributed and exchanged with other RVS users through SIMONE, an Internet based model database.

### 3.2.11 Tools for logging

To assist with their evaluation of the Forsmark and Laxemar sites SKB developed a number of purpose designed tools including Boremap and BIPS described below.

#### 3.2.11.1 Boremap

Detailed consistent geological logging of the cores obtained from the drilling programs was essential for subsequent sampling and borehole investigations as well as for the three-dimensional modelling of the two sites. To ensure consistency of core logging and to provide a direct digital data submission SKB developed the so-called Boremap system. Boremap is software that integrates results from drill core logging, and/or drill cuttings, with video image derived information from BIPS-logging (Borehole Image Processing System) (see below) and calculates the absolute position and orientation of fractures and various planar lithological features intersected (Petersson et al, 2006).

The Boremap software contains the bedrock and mineral standard terminologies (dictionaries to ensure consistent use of terms) used by the Geological Survey of Sweden (SGU) for geological mapping of the surface at the Forsmark site investigation area, to enable direct correlation with the surface geology. To ensure data security during logging data are backed-up via the SKB intranet. The primary data are subsequently exported to the SKB database SICADA. Boremap utilises Geoplot and WellCAD for final data presentation.

#### 3.2.11.2 BIPS - Borehole Image Processing System

In essence BIPS is a high resolution down-hole, colour TV-camera logging system that records depth registered images of the borehole wall

The resolution of the BIPS-image allows the estimation of fracture widths with an error of ± 0.5 millimetres. Thus, reliable measurements of fracture widths/apertures less than 1 millimetre are possible to obtain and the minimum width/aperture given is therefore 0.5 millimetre.

### 3.2.12 Summary of approaches used and their application

Table 6 and Table 7 summarise the methods used in the Forsmark and Laxemar site investigation programmes respectively and what they were used for.

The development of BOREMAP and its application to the two sites investigated by SKB ensured a rigorous and consistent approach to borehole data handling that was invaluable in the development of the 3D geological models of the sites. Modelling and the general development of understanding of the sites was facilitated by the staged development of the site descriptive models (with associated data freezes) that was adopted by SKB.

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Mapping (topographical, geomorphological and geological)** | | Detailed bedrock mapping with special emphasis on fractures. | Fracture statistics (orientation, length) and identification of brittle and ductile features at surface. Input for rock domain, DZ and DFN modelling |
| | | Detailed bedrock mapping of excavations across lineaments | Assessment of the geological character of lineaments. Input especially for DZ modelling, but also DFN |
| | | Comparative geological mapping with the BOREMAP system: | Control of the reproducibility of borehole mapping data |
| | | Production of orthorectified aerial photographs and digital terrain model | Topographic/bathymetric data only used to very limited extent in DZ modelling work after version 1.2 |
| **Nature, distribution and properties of the geological units** | **Geometry and geological structure** | Boremap mapping | Data used in identification of rock type and rock units |
| | | Marine geological survey of the sea bottom off Forsmark | Input for lineament interpretation and subsequent DZ modelling. |
| | | Helicopter-borne, geophysical data (magnetic, EM, VLF and gamma-ray spectrometry data) | Base data for interpretation of airborne magnetic lineaments |
| | | High-resolution seismic reflection data carried out during stage I and II (including interpretation) | Identification of seismic reflectors in the bedrock that may correspond to deformation zones or boundaries between different types of bedrock. Input for DZ modelling. |
| | **Rock properties and composition** | U-Pb, 40Ar/39Ar, (U-Th)/He and Rb-Sr geochronological data from bedrock and fracture minerals (surface and borehole samples) | Input for conceptual understanding of the geological modelling work |
| | | Mineralogical and geochemical analyses of rock types and fracture fillings | Mineralogical and geochemical properties of rock types and fracture fillings. Input for rock domain, DZ and DFN modelling |
| | | Older geological and geophysical data from the Forsmark nuclear power plant and SFR, including seismic refraction data | Rock type data from boreholes and tunnels |
| | | Petrophysical and in situ gamma-ray spectrometric data from rock types | Physical properties of rock types. Input for rock domain modelling. Data also utilised for the interpretation of geophysical logs. |
| | **Mineralogical characterisation of the host rock(s)** | Mineralogy, geochemistry, porosity and redox capacity of altered rock adjacent to fractures | Mineralogical and geochemical properties of rock types. Input for rock domain modelling. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Geological structure** | **Interpretation of structural domains from discontinuity data** | Geophysical logging | Data used in borehole mapping and in single-hole interpretation. Input for both rock domain and DZ modelling. |
| | | Single hole interpretation | Interpretation used in rock domain and DZ modelling |
| | | Older geological and geophysical data from the Forsmark nuclear power plant and SFR, including seismic refraction data | Lineament identification at the nuclear power plant, brittle structures at or close to the surface in the vicinity of the nuclear power plant, and identification of brittle deformation zones. Fracture orientation and mineral coatings from tunnels and boreholes. Input for rock domain, DZ and DFN modelling. |
| | | Radar and BIPS logging, and interpretation of radar logs | Data used in borehole mapping (BIPS) and in single-hole interpretation (radar logging) with focus on identification of brittle deformation zones. Input for both rock domain and Deformation Zone (DZ) modelling. |
| | | Mineralogical and microstructural analyses of vuggy metagranite in | Input for rock domain, fracture domain and DZ modelling |
| | **Fault and deformation zone locations** | Vertical seismic profiling, | Input for DZ modelling |
| | | Characterisation of brittle deformation zones at Forsmark | Input for DZ modelling |
| | | Boremap mapping | Assesses ductile deformation in the bedrock, fracture statistics. Data used to identify brittle deformation zones in single-hole interpretation. Input for rock domain, DZ and DFN modelling |
| | | Interpretation of topographic, bathymetric and helicopter-borne geophysical data. Alternative interpretation in and immediately around the candidate area. Assessment of all lineaments in the target area. | Identification of magnetic lineaments. Input for DZ modelling work |
| | | High-resolution seismic reflection data carried out during stage I and II (including interpretation) | Identification of seismic reflectors in the bedrock that may correspond to deformation zones or boundaries between different types of bedrock. Input for DZ modelling. |
| | | Seismic refraction data | Identification of low velocity anomalies in the bedrock that may correspond to deformation zones. Input for DZ modelling. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Geological structure** | **Fault and deformation zone locations** | Seismic velocity measurements along excavations across lineaments | Identification of low velocity anomalies in the bedrock that may correspond to deformation zones. Input for DZ modelling. |
| | | Ground geophysical data (magnetic and EM data) close to drill sites 1, 2, 3, 4 and 5, and several lineaments (including interpretation) | Identification of magnetic lineaments. Input for DZ modelling |
| | | High-resolution ground magnetic measurements | Identification of magnetic lineaments. Input for DZ modelling |
| | | Mise-à-la-masse data from DS5 | Method test |
| | | Regional gravity data and interpretation | Verification of regional rock domain |

**Table 6** Inventory of all available geological, geophysical, borehole and geotechnical data with an explanation of their useage and handling in the SDM-Site Forsmark modelling (data extracted from SKB (2007)).

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Mapping (topographical, geomorphological and geological)** | | Bedrock mapping – outcrop data | Rock type, rock type distribution, ductile deformation in the bedrock, fracture statistics, and identification of deformation zones at surface. Input for rock domain, DZ and DFN modelling. |
| | | Bedrock geological map | Input for rock domain modelling. |
| | | Detailed bedrock mapping | Fracture statistics (orientation, length) and identification of brittle and ductile features at surface. Input for rock domain, DZ and DFN modelling. |
| | | Digital orthorectified aerial photographs and digital terrain model | Input for lineament identification and subsequent DZ modelling. |
| | | Aerial orthophotos and laser scanning (LIDAR) | Detailed elevation model and orthophotos. Input for lineament identification and subsequent DZ modelling. |
| | | Density logging from selected core-drilled boreholes | Subdivision of Ävrö granite into Ävrö quartz monzodiorite and Ävrö granodiorite. |
| **Nature, distribution and properties of the geological units** | **Geometry and geological structure** | Boremap mapping | Data used in identification of rock type and rock units |
| | | Marine geological survey | Input for lineament interpretation and subsequent DZ modelling. |
| | | Helicopter-borne geophysical data (magnetic, VLF, EM and gamma-ray spectrometry) | Base data for identification of lineaments and subsequent DZ modelling. |
| | | High-resolution seismic reflection data carried out during stage I and II (including interpretation) | Identification of seismic reflectors in the bedrock that may correspond to deformation zones or boundaries between different types of bedrock. Input for DZ modelling. |
| | **Rock properties and composition** | U-Pb, 40Ar/39Ar, (U-Th)/He geochronological data of bedrock and fracture minerals (including samples from drill cores) | Input for conceptual understanding of the geological modelling work. |
| | **Mineralogical characteris-ation of the host rock(s)** | Mineralogical and geochemical analyses of rock types | Mineralogical and geochemical properties of rock types. Input for rock domain modelling. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Geological structure** | **Interpretation of structural domains from discontinuity data** | Geophysical logging | Data used in borehole mapping and in single-hole interpretation. Input for both rock domain and DZ modelling. |
| | | Single hole interpretation | Interpretation used in rock domain and DZ modelling |
| | | Petrophysical and *in situ* gamma-ray spectrometric data of rock types | Input for rock domain modelling. |
| | | Radar and BIPS logging, and interpretation of radar logs | Data used in borehole mapping (BIPS) and in single-hole interpretation (radar logging) with focus on identification of brittle deformation zones. Input for both rock domain and Deformation Zone (DZ) modelling. |
| | | Gravity data (profiles) | Geophysical modelling. Input for rock domain modelling |
| | **Fault and deformation zone locations** | Characterisation of deformation zones | Focussed lineament investigations, MDZ studies and outcrop structural investigations. Input for DZ modelling. |
| | | Characterisation of brittle deformation zones | Input for DZ modelling and geological evolution. |
| | | Calculation of Fracture zone index | Input for DZ modelling. This approach was abandoned by SKB and replaced by a "single hole interpretation", i.e. 1D modelling of borehole information (core+video+sampling+logging etc) |
| | | Seismic refraction data | Identification of low velocity anomalies in the bedrock that may correspond to deformation zones. Input for DZ modelling |
| | | Boremap mapping | Assesses ductile deformation in the bedrock, fracture statistics. Data used to identify brittle deformation zones in single-hole interpretation. Input for rock domain, DZ and DFN modelling |
| | | Interpretation of topographic, bathymetric and helicopter-borne geophysical data including alternative lineament interpretation | Identification of lineaments. Input for DZ modelling. Assessment of dolerite dykes – input to rock domain modelling |
| | | High-resolution seismic reflection data | Identification of seismic reflectors in the bedrock that may correspond to deformation zones or boundaries between different types of bedrock. Input for DZ modelling. |
| | | Ground geophysical data (magnetic and EM data) | Input for DZ modelling. Assessment of possible dolerite dykes |

| *Information requirement* | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|
| **Thermal and density properties of the host rock** | Fluid temperature and density logging from selected core-drilled boreholes | Temperature logging:<br>Description of natural temperature variations with depth. Temperature gradients.<br><br>Density logging:<br>Estimation of thermal conductivity from density based on relationship between these two parameters. Modelling of spatial correlation in thermal conductivity. Subdivision of Ävrö granite into Ävrö quartz monzodiorite and Ävrö granodiorite. |
| | Temperature data from Posiva flow-logging | Description of natural temperature variations with depth. For comparison with fluid temperature loggings. |
| | Boremap mapping | Major and subordinate rock type distribution. Data used as input to stochastic simulation of lithologies. Data also used for rock type identification of drill core samples used for thermal and density measurements. |
| | Laboratory measurements of density | Data used for investigation of relationship between density and thermal conductivity. For Ävrö granite samples, density is used to differentiate Ävrö quartz monzodiorite from Ävrö granodiorite. |
| | Laboratory measurements of thermal properties | Estimation of thermal conductivity, thermal diffusivity and specific heat capacity. |
| | Modal analyses | Estimation of thermal conductivity from mineralogical composition of the bedrock. Impact of alteration on mineralogy and thermal conductivity. |
| | Laboratory tests of thermal expansion | Estimation of the thermal expansion coefficient. |
| | Laboratory tests of thermal properties – surface samples | Estimation of thermal conductivity, thermal diffusivity and specific heat capacity. |
| | Modal analyses – surface samples | Estimation of thermal conductivity from mineralogical composition of the bedrock. |
| | Small-scale field measurements of thermal properties | Estimation of thermal conductivity at a larger scale than for laboratory samples. Analysis of anisotropy in thermal conductivity. |
| **Mechanical and stress data** | Laboratory tests on intact rock:<br>- uniaxial compressive strength (UCS) tests<br>- triaxial compressive strength tests<br>- indirect tensile strength tests | Characterisation of the intact rock; empirical determination of the rock mass mechanical properties by means of Q and RMR; theoretical determination of the rock mass mechanical properties by means of numerical modelling. |

| *Information requirement* | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|
| **Mechanical and stress data (cont.)** | Laboratory tests on fractures:<br>- tilt tests on fractures<br>- shear tests on open fractures, methods I- III | Characterisation of the fracture properties and of the rock mass by Q and RMR.<br>Characterisation of the fractures – strength and stiffness; theoretical determination of the rock mass mechanical properties by means of numerical modelling. |
| | Direct stress measurements:<br>- overcoring (OC)<br>- hydraulic fracturing (HF)<br>- hydraulic fracturing on pre-existing fractures (HTPF)<br>Indirect stress data: borehole breakout | Estimation of the in situ stress field. |
| **Hydrogeological data** | ***Geometrical and topographical data***<br>Digital Elevation Model (DEM) | Basic input to flow and mass transport models, descriptions and modelling of the marine ecosystem. |
| | ***Geological data***<br>Map and model of Quaternary deposits in the terrestrial part and sea bottom of the Simpevarp regional model area, Rock types, Bedrock model, geometry | Basic input to flow and mass transport models, descriptions and modelling of the marine ecosystem. |
| | ***Cored borehole data***<br>Wireline tests, boreholes, drilling information) | Borehole data and (prel) transmissivity distribution in large scale. |
| | Difference flow logging | Conductive parts of the borehole, statistics of conductive fractures. |
| | Correlation difference flow logging and core mapping | Conductive parts of the borehole, base for orientation of conductive fractures for usage in the hydrogeological DFN. |
| | Hydraulic injection tests, pumping tests (single hole) | Transmissivity distribution along the borehole in different scales. |
| | ***Percussion hole data***<br>Drilling and hydraulic tests | Hydraulic test data for the bedrock. |
| | ***Standpipes in QD deposits data***<br>Drilling | Standpipes geometry used in the flow modelling.<br>Description of stratigraphical distribution and total depth of overburden in the terrestrial parts of the Simpevarp and Laxemar subareas. |
| | Interference tests using percussion and core holes | Infer connectivity between deformation zones and estimate transmissivity and (if possible) storage coefficient for deformation zones. |
| | Other borehole, construction, tunnel data and models | Previous made evaluations compared to new data and for assessment of properties not known or with few data from SI. |

| *Information requirement* | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|
| **Hydrogeological data** | Meteorological and hydrological data from surrounding stations prior to and during the site investigations | General description of hydrology, comparison with site investigation data. |
| **Hydrogeochemical data** | ***Surface water data*** Precipitation, running water, soil pipes, sea water samples, precipitation gauges, SMM-drill cores. Surface water sampling | Delineation and general characteristics of Meteoric water, end-member and surface water recharge. Discharge pattern in surface areas. Explorative analyses and modelling. Characterisation and description of spatial and temporal variability of surface water chemistry. |
| | Shallow groundwater sampling | Description of the input of shallow groundwater endmember to the bedrock. |
| | ***Groundwater – cored and percussion boreholes*** Cored boreholes – intermediate to deep groundwater. Complete chemical sampling and characterisation (class 4 and 5) and hydrochemical logging. Percussion boreholes | Explorative analyses, which involves manual evaluation and mathematical modelling such as PHREEQC, M3 and coupled transport modelling. The results providing the basis to the conceptual model of the site. The use of the data in the specific modelling approaches are described in SKB R-08-93. Description of groundwater types and their distribution at various depth intervals. Regional and spatial distribution of groundwater types. Chemical character of all the groundwater types. |
| | Hydrochemical monitoring programme for core and hammer drilled boreholes 2007. | Chemical changes during time series sampling and variability check. |
| | Porewater data | Delineate the porewater chemistry and isotope compositions. Used for studies of interaction between the fracture water and porewater. Support to the general palaeo understanding of the site. Important input for the hydrogeological modelling. |
| | ***Microbial, colloidal and gas data*** Sampling of microbes, colloids and gases | General and detail description of microbes, colloids and gases. Redox reaction support, and important input to safety assessment. |
| | ***Fracture mineral data*** Open and closed fractures | Mineral characterisation. Identification of redox-sensitive minerals. Estimation of redox-capacity and redox sensitive minerals. Origin and age determination of calcite fracture fillings. Support for the palaeounderstanding of the site. |

| *Information requirement* | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|
| **Bedrock transport properties data** | Laboratory measurements of porosity, effective diffusivity (formation factor), BET-surface areas, and sorption | Assignment of corresponding material property parameters in retardation model. |
| | Laboratory measurements of rock formation factors by AC electrical resistivity method | Comparative measurements of formation factors used in retardation model. |
| | *In situ* measurements of formation factors by AC electrical resistivity method | Comparative measurements and alternative parameterisation for rock formation factors used in retardation model. |
| | Quantitative distribution of fracture minerals | Development of "fracture type" classifications used in retardation model. |
| | PMMA-measurements of porosity distribution and heterogeneity | Porosity estimation for deformation zone structural elements used in retardation model. Supporting argumentation for existence of increased porosity in vicinity of fracture surfaces. |
| | Pore water characterisation and diffusion experiments | Supporting argumentation for the existence of a connected rock matrix porosity and qualitative assessment of uncertainty related to *in situ* formation factors. |
| | Rock matrix permeability measurements, microcrack volume measurements | Supporting argumentation for existence of *in situ* compression of pore spaces. |
| | Groundwater flow monitoring in permanently installed boreholes using tracer dilution method | Measurement of *in situ* flow rates under non-pumped conditions and estimations of local hydraulic gradients. |
| | Groundwater flow measurements using tracer dilution method and SWIW tests | Partial confirmation of the existence of retardation processes consistent with premises of transport model. Tracer dilution data used to provide estimates of local hydraulic gradients. |
| | Multiple well tracer tests | Partial confirmation of the existence of retardation processes consistent with premises of transport model.<br>Tracer dilution data used to provide estimates of local hydraulic gradients. |
| **Abiotic data for the surface system** | Surveying of streams | Description of stream characteristics. Input to quantitative water flow modelling (MIKE SHE). |
| | Map of Quaternary deposits in the terrestrial part of the Simpevarp regional model area | Description of surface distribution of Quaternary deposits in the terrestrial part of the regional model area. |
| | Maps of Quaternary deposits covering a large part of the sea bottom in the regional model area | Description of surface distribution of Quaternary deposits at the sea floor. |
| | Map of soils in the terrestrial part of the Simpevarp regional model area | Distribution of soil types in the regional model area. |

| *Information requirement* | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|
| **Abiotic data for the surface system** | Deposits on the bottom of watercourses | Evaluation of the map of Quaternary deposits. |
| | Stratigraphical studies in machine cut trenches | Stratigraphy and total depth of Quaternary deposits. |
| | Drilling and sampling of Quaternary deposits | Description of stratigraphical distribution and total depth of overburden in the terrestrial parts of the Simpevarp and Laxemar subareas. |
| | Helicopter borne survey data | Description of surface distribution of Quaternary deposits in parts of the Simpevarp regional model area. |
| | Resistivity measurements: refraction seismic | Total depth of Quaternary deposits. |
| | Chemical and mineralogical analyses of Quaternary deposits | Chemical and mineralogical properties of Quaternary deposits. |
| | Physical analyses of Quaternary deposits | Physical properties of Quaternary deposits. |
| | Dating of sediment and peat | Accumulation rates of sediment and peat. |
| | ***Meteorological data;*** ***Regional data*** Meteorological data from surrounding stations prior to and during the site investigations | General description of meteorology, comparison with site investigation data. |
| | ***Meteorological data;*** ***Site investigation data*** Meteorological data from the stations on Äspö (Sep. 2003-Aug. 2007) and in Plittorp (Jul. 2004–Aug. 2007); Sicada data up to Dec. 2007 are used. | Description of meteorology and comparison with data from surrounding stations. Input to quantitative water flow modelling (MIKE SHE). |
| | Hydrological data from surrounding hydrological stations prior to and during (Sicada data only) the site investigations | General description of hydrology. Comparison with site investigation data. |
| | Investigation of potential locations for hydrological stations | Size of catchment areas for manual and automatic surface-water discharge measurements. |
| | Geometrical data and descriptions of catchment areas, lakes and streams | Delineation and general characteristics of catchment areas, lakes and streams. Input to quantitative water flow modelling (MIKE SHE). |
| | Manual discharge measurements in streams | Description of spatial and temporal variability of surface-water discharge. |
| | Monitoring of surface-water discharges in streams | Description of spatial and temporal variability of surface-water discharge. Calculation of specific discharge. Calibration of quantitative water flow models (MIKE SHE). |
| | Monitoring of surface-water levels in lakes and the sea | Description of spatial and temporal variability of surface-water levels. Input to quantitative water flow modelling (MIKE SHE). |
| | Characterisation of streams, including vegetation, bottom substrate and technical encroachments | Description of streams and land improvement and drainage operations. |

| *Information requirement* | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|
| **Abiotic data for the surface system** | Field checks of streams and land improvement and drainage operations | Description of streams and land improvement and drainage operations. Input to quantitative water flow modelling (MIKE SHE). |
| | Hydrogeological inventory in the Oskarshamn area | General description of hydrogeology, water operation permits and land improvement and drainage operations. |
| | Inventory of private wells | General description of private wells. |
| | Geological data from drilling in QD and installation of groundwater monitoring wells | Conceptual hydrogeological model. |
| | Hydraulic conductivity from slug tests in groundwater monitoring wells | Conceptual hydrogeological model. Hydrogeological parameterisation of the QD. |
| | Hydraulic conductivity from particle-size distribution curves. Hydraulic conductivity and storage-properties data from single-hole and interference tests in groundwater monitoring wells. Hydraulic interference and tracer tests in percussion boreholes and groundwater monitoring wells. Groundwater flow velocities from tracer dilution tests in groundwater monitoring wells | Conceptual hydrogeological model. Hydrogeological parameterisation of the QD. |
| | ***Oceanographical data*** Regional oceanographical data | Description of coastal basins. Quantitative modelling. |
| | ***Chemistry data***<br>Surface water sampling<br>Shallow groundwater<br>Chemical composition of biota and deposits overburden<br>Sediment, suspended material and porewater | Modelling; characterisation and description of spatial and temporal variability of surface water chemistry. Characterisation of the chemistry in shallow groundwater. Characterisation of the chemistry of the Quaternary deposits. |
| **Other data** | Population surveys for wildlife, including birds, mammals, marine biota and fish. Also, vegetation, biomass and ecosystem surveys | Ecosystem modelling. |

**Table 7** Inventory of all available geophysical, geological, thermal, mechanical, geotechnical, hydrogeological, and hydrogeochemical data as well as in-situ and laboratory based material testing methods, with an explanation of their useage and handling in the SDM-Site Laxemar modelling (data extracted from SKB (2009), source references also given in this report).

## 3.3 THE POSIVA OLKILUOTO EXAMPLE

The principal goal of the preliminary investigations was to characterise the candidate sites to the extent needed to judge that its suitability could be confirmed. It is considered both unnecessary and unrealistic to search for the best site.

The overall approach used for the identification of possible targets for a repository was based on the crush-tectonic block structure model of Finnish bedrock. All bedrock in Finland is broken down into blocks separated by crush (or shear) zones, the length of which may be many tens of kilometres. These blocks are, in turn, divided into sub-blocks by smaller scale discontinuities. The approach adopted by Posiva (and SKB) is that if a repository is developed in the interior of a block, its integrity will not be compromised by future tectonic activity. In other words, potentially damaging rock deformation is likely to be focussed in the shear zones, leaving the material in the interior of the blocks largely unaffected (Vira, 1995).

The investigations at each site involved drilling and sampling, geophysical, hydrogeological, chemical, mineralogical and rock mechanics studies, and modelling of both bedrock structure and groundwater movement. The results of the preliminary site investigations were submitted to the Finnish authorities at the end of 1992 (YJT, 1992a). No exceptional features were noted that would compromise the siting of a repository at any of the four sites. In order to focus the field activities further, it was decided to restrict detailed site investigation to candidate sites in three municipalities: Kuhmo, Eurajoki and Äänekoski. The choice was made largely on the basis of the practicality of site investigation.

By 1999, detailed site investigations had been completed in four areas. Geological mapping and geophysical surveys (airborne and surface) were carried out at all sites. A comprehensive geophysical logging programme was carried out in the boreholes, including fluid logs, resistivity, radiometric, acoustic and tube-wave logs, together with borehole radar and VSP measurements. Given that the geology was considered suitable at all four sites evaluated, in 1999 Posiva applied for Government approval to develop a spent fuel repository at Olkiluoto because non-geological factors made this site the most preferable. The Finnish Government confirmed this choice in 2000 (Uranium Institute 2000).

### 3.3.1 Basement rocks - nature, distribution and properties

A series of Site Reports have been produced describing the geology of the area with the third version published in 2009 (Posiva report 09-01 – Posiva 2009). This version has developed an updated version of the descriptive model of the site which describes the geometry, properties of the bedrock and the water and associated interacting processes and mechanisms

The most important requirement of the investigations is a thorough understanding of the hydrogeology at each potential site, since radionuclides may be transported away from the repository in groundwater. Detailed knowledge of rock fracturing (to depths of at least 1000m), local geology and structure is therefore required, these features also have an important bearing on the technical design and the general stability of the eventual repository.

A broad range of disciplines have been involved in the investigations to date. These included geological/structural mapping, airborne-, surface- and borehole geophysics, core characterisation, etc. The integration of all the resulting data sets has yielded what is believed to be the most sound conceptual model of geological conditions at the site.

Airborne and ground geophysics were considered an essential component of the investigations at all the Finnish sites because of the general lack of bedrock exposure. In addition to their role in mapping lithological type and structural features (fracture zones etc), geophysical techniques were also employed to confirm the absence of potentially economic ore deposits.

3D reflection seismic investigations have been carried out in two campaigns, the first a pilot study in 2006 in the ONKALO area and the second in 2007, which is a more extensive investigation of the eastern area. The interpretation of these surveys provided direct information on dipping reflecting structures and indirect indications of vertical features. Additionally, a 2D high resolution reflection seismic survey (HIRE) was carried out on the roads at Olkiluoto and continuing to the villages of Hankkila, Sorkka and Linnamaa. A crosshole tomographic test using radiowave imaging between drillholes OL-KR4 and OL-KR10 showed promising results (Korpisalo et al. 2008) and will be investigated further in other deep drillholes and in characterisation drillholes (Posiva 2009).

By 2004, several geophysical surveys had been carried out in the Olkiluoto area from the air, on the ground and in boreholes (Posiva Report 2005-3). Particular attention was given to the development of a 3D geological model of the site area by bringing together different geophysical data, particularly by simultaneously examining data from different survey times in the previous 10-15 years. Attention was also given to carrying out ground based geophysical surveys. A systematic series of refraction seismic surveys were carried out to obtain information on the continuation of different structures (fracture zones) both on the surface and between boreholes. More electromagnetic and electrical sounding surveys were also carried out on lines crossing the entire site area which provided more detailed information on the geology. Seismic surveys (VSP, crosshole and walk-away seismic) were also carried out and combined interpretations with other geophysical data also took place.

### 3.3.2 Superficial (drift) deposits - nature, distribution and properties

The Olkiluoto site has low relief (maximum 15 m) and is largely covered by soils, typically sandy till with some rocks and boulders, typically between 2 - 5 m thick but up to a maximum of 16m. Clays and peat deposits are rare. Posiva have mapped the extents and types of overburden using test pits, some cored samples, boreholes and geophysical surveys. The latter included seismic and ground-penetrating radar (GPR) surveys. The results of the refraction seismic survey were used to interpret overburden thickness from rock head picks. The GPR survey was undertaken to map the thickness of the peat layers in the overburden and to provide information on the degree of fracturing of the bedrock surface but because of the conductive nature of the overburden was unable to image the bedrock surface (Lahdenperä et al 2005).

Overburden thickness was modelled using bedrock surface models and surface topography controlled by data from trial pits and boreholes where these were available (Vaittinen et al. 2003).

### 3.3.3 Geological structure

There are three main fracture trends identified in the Olkiluoto area and these may be distinguished topographically as elongated surface depressions. The fractures are mainly steeply dipping. Most are tight or filled with calcite, kaolinite, illite and pyrite, but some are open. Typical of crystalline, hard rock environments, the intensity of fracturing decreases with depth.

Results from geophysical 3D imaging of rock properties (VSP, magnetic, electromagnetic (Slingram, Gefinex 400S) and mise-à-la-masse (charged potential)) were used to help both the lithological and structural modelling of both the ONKALO and site areas. Geophysical interpretations were used in particular to investigate the continuity and orientation of several structures.

New mise-à-la-masse surveys were also carried out during 2005 and in the beginning of 2006 to produce more information concerning previously identified structures. The conductive zones identified by the mise-à-la-masse surveying seem to be correlated with modelled hydrogeological features. These surveys also made it possible to establish the likely locations of outcrops of some of the major fracture zones.

A small mise-à-la-masse test survey was carried out in the ONKALO at the beginning of 2006 to determine the potential for using this method to examine the continuation of so-called long fractures (single fractures) in the tunnel, from the tunnel to the ground surface and to the drillholes near the tunnel. The results are still being evaluated, but preliminary results suggest that this method seems to work well at this scale.

In drillholes OL-KR1, OL-KR4 and OL-KR27 gamma spectrometer surveys were carried out during 2005 to see whether this method could be used to define the alteration properties of the rock. Electromagnetic soundings (Gefinex 400S) have been carried out annually since 2004 at fixed stations in the ONKALO area for monitoring possible changes in the conductivity of the bedrock (i.e. because of potential changes in the level of saline groundwater).  No changes were detected by 2006.

### 3.3.4 Mineral deposits

The authors are not aware that there are any mineral deposits in the vicinity of the Olkiluoto site. Posiva undertook an evaluation of the airborne and surface geophysics data to confirm the absence of ore deposits.

### 3.3.5 Summary of approaches used and their application

Table 8 summarises the methods used in the Olkiluoto evaluation programme and what they were used for.

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Mapping (topographical, geomorphological and geological)** | | Surface geological mapping (structural and lithological)<br><br>- outcrop mapping<br>- investigation trenches<br>- mapping of Quaternary deposits | Mapping of lithologies, ductile deformation structures, fractures and brittle deformation zones.<br>These methods are used to characterise bedrock properties, and to gather information from overburden/ Quaternary deposits<br>Used to build a 2D and 3D lithological model and feed into a conceptual geological model. |
| **Nature, distribution and properties of the sedimentary rock succession.** | | Airborne geophysical surveys (prior to 1999) | Results have been used in lithological and structural modelling at both the ONKALO and site scales. |
| | | Ground geophysical data (surveyed prior to 1999) | Results have been used in lithological and structural modelling at both the ONKALO and site scales. |
| | | Geophysical methods used in borehole surveys (surveyed prior to 1999) | Geophysical logging data from boreholes are used to support lithological and structural modelling |
| | | Airborne and ground geophysics measurements and investigations carried out in 2006-2008, at surface and at ONKALO | Used for further refinement of the conceptual model of geological conditions |
| **Nature, distribution and properties of the sedimentary rock succession.** | | Downhole geophysical measurements and investigations carried out in 2006-2008 at surface and at ONKALO | Used for further refinement of the conceptual model of geological conditions |
| | | Tunnel and downhole geophysics work in underground drillholes geophysical investigation activities. | Used for further refinement of the conceptual model of geological conditions |
| | | Drilling and sampling in shallow and deep boreholes<br>- drillhole imaging<br>- core characterisation,<br>- geological logging of the drillcore | Used to build the 2D and 3D lithological model, and conceptual geological model. Modelling of the bedrock structure |
| **Geological structure** | **Locations of faults and deformation zones** | Airborne geophysical surveys (prior to 1999) | Geophysical interpretations were used in particular for examining the continuity and orientation of the deformation structures. |
| | | Ground geophysical data (surveyed prior to 1999) | Geophysical interpretations were used in particular for examining the continuity and orientation of the deformation structures. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Tectonics and measurements of regional stress field** | | Microseismic (MS) monitoring since 2002 and GPS measurements since 1995 on a continuous basis | Monitoring of long-term seismicity and stress changes. |
| | | ONKALO stress measurement campaign<br>Using overcoring (OC) method (CSIRO cell) in drillholes | Measurement of the stress field |
| | | Rock response measurements<br>-convergence measurements (using convergence bolts) and extensometer measurements in shafts within the ONKALO<br>- strain measurements using strain gauges on the ventilation shaft (stress release method) | To obtain the orientation of the horizontal in situ stress field and to estimate the magnitudes of the horizontal principal stresses. These tests were conducted in two shafts at the ONKALO |
| **Geomechanical properties of the host rock** | **Deformation characteristics** | Stress-induced damage observations – visual assessment of rock exposed in ONKALO tunnels | Monitoring – collection of visual evidence of deformation to assess affects of construction. |
| | | Testing of natural rock fractures – (LVDT test apparatus) | Used to determine the shear strength properties of natural rock fractures at site |
| | **Geotechnical and engineering properties of the host rock(s)** | Geological mapping in the ONKALO (tunnel mapping)<br>*Observations/measurements;*<br>- chainage<br>- rock type<br>- grain size<br>- Rock Quality Designation (RQD)<br>- joint set number (Jn)<br>- 10-20 main fractures<br>- fracture length over 1 metre<br>- fracture orientation (dip and dip direction)<br>- joint roughness number (Jr) andJoint alteration number (Ja)<br>- joint water reduction factor (Jw)<br>- stress reduction factor (SRF) | These measurements allow the mechanical properties of fractures, brittle deformation zones and the rock mass to be evaluated. The provisional appraisal of rock quality can also be assessed.<br><br>These data are used for planning rock reinforcement, for geological and rock mechanical modeling, and also for prediction-outcome studies. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Geomechanical properties of the host rock** | **Geotechnical and engineering properties of the host rock(s)** | Schmidt hammer tests in shafts on intact rock and fracture surfaces<br>Point load tests on cores from pilot holes and on illitised (altered) cores | Determination of the rock's geotechnical properties |
| | | Core discing (CD) observations from existing deep drillholes (OL-KR1 – OLKR48) have been recorded. One drillhole OL-KR10 was also analysed to identify possible stress-induced breakouts and drilling-induced fractures | Analysis of rock behaviour under stress and effects of excavations |
| | | Measurement of rock mechanical properties;<br>- rock stress<br>- mechanical properties of the intact rock<br>- thermal properties of the intact rock<br>- mechanical properties of fractures<br>- mechanical properties of deformation zones<br>- mechanical properties of the rock mass<br>- MS and GPS and surface levelling measurements | Determination of the rock's thermal, mechanical, and stress properties. Used to provide parameters for modelling studies and to assess the likely behaviour of the rock at site. |
| | **Prediction of long term behaviour** | Temperature logs; in drillholes, long term temperature monitoring | Determination of the rock's thermal properties, and monitoring of long term changes |
| **Hydrogeology** | **Hydrogeological monitoring and surface measurements** | Hydrogeological measurements at four measuring weirs | Determination of surface runoff of the local catchment areas |
| | | Long-term monitoring of the groundwater table | Characterisation of hydrogeological conditions. Used to refine hydrogeological model, to identify and model the hydrogeological zones. |
| | | Hydrological monitoring programme<br>*Measurements taken with instruments on surface and in boreholes;*<br>- precipitation<br>- run-off<br>-sea water table level<br>-infiltration<br>- soil frost<br>- groundwater level and hydraulic head<br>- flow conditions<br>- hydraulic conductivity<br>- in situ EC (gw salinity)<br>- leakage of gw into tunnels<br>- hydrological/water balance | Measures short- and long-term effects in hydraulic head<br><br>To follow the evolution of the site, both underground and on the surface, during and after the construction of the ONKALO. |

| **Information requirement** | | ***Method of measurement*** | ***Interpretation and modelling method*** |
|---|---|---|---|
| **Hydrogeology** | **Hydrology of the geological formations** | Hydrogeological measurements in boreholes<br>- flow measurements<br>- pressure build-up test<br>- water injection test<br>- water loss test-(Lugeon test) | Parameters are obtained for groundwater numerical modelling |
| | | Drilling and sampling in shallow and deep boreholes<br>- drillhole imaging<br>- core characterisation,<br>- geological logging of the drillcore | Used for modelling of groundwater movement |
| | | Measurement of hydraulic head and hydraulic conductivity<br>(using difference flow meter, transverse flow measurements, Hydraulic Testing Unit tool (HTU) - slug tests, cross hole flow measurements) | Used for interpreting hydraulic connections between drillholes, to refine hydrogeological model and to identify and model the hydrogeological zones.<br>Hydraulic conductivity investigations measure the transmissivity distribution, and fresh water head of hydraulically-conductive fractures. |
| | | Multi-packer systems in boreholes | Results of multi packer tests are input to numerical flow modelling |
| | | EC of borehole water and groundwater from specific selected fractures has been measured, as well as the temperature of the water and the single point resistance of the borehole wall | Characterisation of hydrogeological and-geochemical conditions in the bedrock. The data are also used to adjust the hydrogeological and geochemical conceptual models of the site. |
| | | Flow and electric conductivity measurements during long-term pumping | To obtain data on how flow and salinity changes in conditions rather similar compared to the effects that will be due to the ONKALO. |
| | | Hydraulic interference tests - in injection holes | To obtain data on hydraulic connections at detailed scale (1-10m) |
| | **Geochemistry of groundwater** | Groundwater sampling of shallow groundwaters<br>- Using groundwater tubes (PVP) and shallow drillholes | Geochemistry of the shallow groundwaters – parameters for modelling<br>Monitoring of the seasonal changes and the influence of different construction works at the site. |
| | | Groundwater sampling<br>- in deep open drillholes<br>- multi-packer testing in deep drillholes | General site characterisation in the northern and eastern parts of Olkiluoto.<br>Monitoring of the changes caused by ONKALO construction |
| | | Long term pumping test | Monitoring the effects of long-term pumping on groundwater chemistry |
| | | Matrix pore water studies | Hydrogeochemical characterisation of non-transmissive bedrock.<br>Palaeohydrogeological studies |
| | | Colloid studies | Characterisation of species and amounts of colloids, significant for radionuclide migration. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Hydrogeology** | **Geochemistry of groundwater** | Humus and fulvic acid studies | Characterisation of dissolved organic compounds |
| | | Microbial sampling from deep drillholes and from ONKALO | Site characterisation and specific information of detailed hydrogeochemical conditions.<br>Knowledge of the existing microbes and microbiological processes. |
| | | Groundwater sampling from ONKALO<br>Sampling of low transmissive fractures. | Results used for detailed site characterisation.<br>Monitoring of the changes caused by the ONKALO construction.<br>Monitoring of cement-water interaction. |
| **Radionuclide diffusion potential** | | Groundwater geochemistry studies | Groundwater chemistry has a significant affect on radionuclide transport potential. |
| **Long term stability of the repository** | **Studies in underground laboratory** | Stress-induced damage observations – visual assessment of rock exposed in ONKALO tunnels | Monitoring – collection of visual evidence of deformation to assess affects of construction. |
| | **From surface-based investigations at Olkiluoto (including drillholes).** | Measurement of rock mechanical properties;<br>- rock stress<br>- mechanical properties of the intact rock<br>- thermal properties of the intact rock<br>- mechanical properties of fractures<br>- mechanical properties of deformation zones<br>- mechanical properties of the rock mass<br>- MS and GPS and surface levelling measurements | Used in modelling studies to assess the likely behaviour of the rock at site. |
| **Long term stability of the repository** | **Characterisation of the Excavation Disturbed Zone (EDZ)** | Characterisation methods;<br>- mise-a-la-masse<br>- misfire analysis of the ONKALO excavation rounds (seismic test)<br>- tunnel seismic<br>- Ground Penetrating Radar<br>- vibration measurements<br>- core drilling<br>- block extractions<br>- small-scale Water Loss measurements<br>- PMMA<br>- ultrasonic tests | Characterisation of the EDZ, to understand the likely effect of construction on local geological conditions and to assess the safety and long term performance of the repository. |

**Table 8** Summary of investigations undertaken by Posiva with an explanation of their use for characterisation of the Olkiluoto site, including studies undertaken at the ONKALO rock characterisation facility at Olkiluoto. Summarised and taken from Posiva Report 2009-01. *Assessment Report: General Summary.*

## 3.4 THE ANDRA BURE EXAMPLE

### 3.4.1 Introduction

Andra, the French authority responsible for the management of radioactive waste in France, have considered options for disposal in both clay and granite formations. They summarised the results of the two parallel research programmes in two reports published in 2005, Dossier "2005 Argile" covering a clay hosted repository and Dossier "2005 Granite" a 'granite' hosted repository (Andra 2005a and 2005b). The former is based on a specific site, near Bure on the border between the Haute Marne and Meuse departments, which Andra had been investigating for about 20 years while the latter is based on generic assessments and is not site specific. Only the work at the Bure site is considered here. The Bure site is situated in the eastern Paris Basin some 250 Km east of Paris.

Geologically the area comprises a thick succession of Jurassic strata overlying Triassic strata to the south of the London-Brabant Massif. The Jurassic strata consist of calcareous and clay rich sediments that were deposited in an open and calm marine environment a long way from sediment sources to the north and north-east. The potential repository horizon is the Collovo-Oxfordian clay (COx), which in the vicinity of Bure is from 120 to 160m thick, and has been selected because of its high clay content and low hydraulic conductivity.

In 1999 Andra received approval for the development of an underground research facility at Bure and have developed a URL in the COx at a depth of 490m as part of their evaluation of the site. While the URL will not become part of a future repository it is close to the areas that is being considered. As part of the work associated with the URL Andra re-evaluated the information from 68 existing boreholes and drilled 40 new boreholes comprising 25 Km with 3,800 cored metres that were focussed on the COx.

### 3.4.2 Mapping (topographical, geomorphological and geological)

#### 3.4.2.1 Topography

For topographic purposes Andra has purchased detailed digital terrain model (DTM) from the Institut Géographique National (IGN), the French national topographic survey. This data is used directly in geological modelling and visualisation applications. Andra also utilises vertical colour aerial photographs that have been georectified and seamlessly mosaiced to form a layer that can by used, for example, to drape over the topographic DTM in visualisations or as a layer in a GIS.

#### 3.4.2.2 Geological Mapping

The area was geologically mapped by the Bureau de Recherches Géologiques et Minières (BRGM), the French national geological survey, in the 1960s as part of their work programme This has been updated by Andra undertaking additional mapping. The geology of the area around Bure was previously very well documented because of past hydrocarbon and water exploration.

#### 3.4.2.3 Geomorphological Mapping

The authors are not aware of any specific geomorphological mapping undertaken by Andra. The area has not been glaciated and has limited superficial deposits (mainly residual 'insoluables' from the limestones and some this accumulations of possibly loessic silts).

### 3.4.3 Sedimentary rocks - nature, distribution and properties

Andra have made extensive use of 2D and 3D seismic survey methods during their investigations in the Bure area as well as a re-interpretation of existing 2D seismic data acquired during hydrocarbon exploration, the latter covering an area of around 60 x 60 Km to the east of St Dizier acquired prior to 1994.

The first 2D survey was done at an early stage in the investigations during 1994/1996. In order to site the URL a 3D seismic survey was undertaken in 1999. This survey covered an area of 4 $Km^2$ centred where the URL is now situated. This survey confirmed the suitability of the site for the URL and identified no faults with a throw greater than ≥2 m (the limit of resolution of the survey).

In 2006/2007 174 line kilometres of 2D seismic survey was acquired in the 250 $Km^2$ transposition zone within which a repository was likely to be situated. This approximately equates to the District used by Nirex. This was designed to provide detailed information on the COx and any faults in the area to allow the selection of a potential repository site. The survey included coverage of the Fosse de Gondrecourt, the Fosse de la Marne and the Fosse de Joinville grabens and associated faulting which bound the Transposition Zone to the southeast and southwest.

In 2010 Andra commissioned a new 3D seismic survey within the Transposition Zone covering an area of 37 $Km^2$ around the 28.5 $Km^2$ Zone d'Intérêt pour la Reconnaissance Approfondie (ZIRA - Underground interest area), about 15 $Km^2$ of which will be selected to host the repository. The survey was acquired between the 17$^{th}$ May 2010 and 29$^{th}$ July 2010 and post acquisition data processing then undertaken during the rest of 2010.

The survey was undertaken with a regular grid in open farmland (3m wide lines were made through the growing crops 25m apart) but in woodland tree cutting was not permitted so lines were made using existing tracks, firebreak etc and scrub clearance as appropriate but this resulted in a less regular grid and variation in orientation when compared to the grid on open farmland.

The aim of the survey was to provide a non-intrusive evaluation of the area short listed to host the repository. Principal objectives were to:

- Identify faults locations
- Determine the geometry of the host rock and overlying formations (depth, thickness)
- Provide a qualitative and quantitative assessment of lithological variability at the resolution of the future underground installations (~10 m).

Interpretation of the survey (up to June 2011) has been aimed at:

- Structural interpretation
- Stratigraphic inversion
- Surrounding formation characterisation

- Qualitative analysis of Callovo-Oxfordian variability

Andra are undertaking further seismic interpretation including inversion to assess variability within the COx, particularly clay content which is due for completion in mid 2012.

Following the initial interpretation of the 3D seismic survey data Andra are confident that within the ZIRA the COx does not show any structural disturbances that would make any part of the area unsuitable for the development of a repository.

In discussions at Bure (June 2011), the Andra team (Béatrice YVEN and Sarah DEWONCK) confirmed that 3D seismic survey was their most useful non-invasive means of evaluating the repository site. During their investigations of the area around Bure Andra have not made extensive use of non-seismic geophysics methods. An aeromagnetic survey was flown and, prior to work on the surface installations of the Meurse/Haute-Marne URLa 'light' micro-gravity survey was undertaken (P. LANDAIS pers. com).

### 3.4.4 Superficial (drift) deposits - nature, distribution and properties

Because the area has not been glaciated there are only limited amounts of superficial deposits in the Bure area. The authors are not aware of a specific superficial mapping undertaken by Andra.

### 3.4.5 Geological structure

There is a 2000 to 3000 m thick Mesozoic sedimentary succession with regional dip of between 1° and 1.5° NW. Overall the sedimentary basin is a simple monoclinal structure.

There is a graben structure to the east of Bure, the Fosse de Gondrecourt, which forms the eastern boundary of the area under consideration, while to the west and south-west are the Fosse de la Marne and Fosse de Joinville grabens and associated faulting. The area under consideration for a repository has few mapped faults. There is a shallow synclinal structure (the Savonniers-en-Perthois Syncline) in the north of the area.

Andra use GoCAD as their primary geological modelling tool. A 3D geological model of an area around the transposition zone, including the grabens to the southeast and southwest, including mapped faults and major sedimentary unit boundaries has been constructed. The primary sources of data for this model are the 2D and 3D seismic survey data, geological mapping information and core and wireline information from the boreholes with the DTM used for topography.

Since the development of the URL Andra have been developing their models of the area iteratively to examine the distribution of rock properties in the COx, including thickness and dip but in particular petrophysical approaches to understanding the distribution of porosity in the host rock.

The data from the 2010 3D seismic survey has been particularly important in developing understanding of rock property distributions and fault geometries in the ZIRA and surrounding areas. It has allowed a more robust and detailed structural model to be developed with excellent control. Petrophysical and mineralogical modelling of the COx formation includes estimation of porosity and P wave velocities in the Transposition Zone and the ZIRA. This has included estimation of the clay, carbonate and silicate content and their distribution within both these areas. The resulting models have allowed Andra to demonstrate the low variability of the IMA (the host unit within the COx proposed for the vaults and drifts of the repository).

### 3.4.6 Mineral deposits

Shallow workings for iron ore exist in the Bure area. These are believed to be largely small open pit workings of limited size and, if any present, underground workings are shallow. Because these are not considered significant in terms of a repository at a depth of 450 to 500 metres these workings have not been considered further by Andra.

The area has been explored for hydrocarbons and a number of exploration wells drilled in the region but no hydrocarbon found. Information from this exploration has been utilised by Andra in their assessment of the Bure area.

### 3.4.7 Spatial heterogeneity

Following the detailed 3D seismic survey undertaken in 2010 Andra have commissioned contractors to undertake inversion of the data. This is to provide detailed information on the distribution of 'shale' within the COx (a 3D model of the clay content of the potential host rock and the surrounding formation) and porosity distribution in the overlying more permeable horizons. By these methods Andra hope to model spatial heterogeneity within the potential host horizon. This work is ongoing at the time of writing and is scheduled to be completed in early summer 2012.

### 3.4.8 Visualisation

In conjunction with BGS, Andra have been developing the use of GeoVisionary as their 3D visualisation system for use in their repository project. They have two aims for the tool. Firstly to provide desk top access by all staff to the geological models and, through the models and visualisations of the borehole trajectories and the URL, to all data in their data base systems. Secondly they are developing the tool to allow visualisations that will be used as part of their stakeholder engagement programme in 2012-2013. This includes the topography, geological models, the URL and the various designs of the potential repository. Visualisations of surface developments etc associated with the building of a repository will be incorporated into the system which will allow local stakeholders to see the impact of the repository on their property etc.

GeoVisionary acts as an umbrella 3D visualisation system for all their data from various sources; principally Andra's Geo database, which holds samples and geoscientific data and SAGD, a database which holds all the real-time experimental data collected from thousands of sensors in numerous drifts and bore holes. These include the topography, geological models, the URL and the various designs of the potential repository. Andra have created an information rich, 2,000 square kilometre GeoVisionary model centred round the Meuse/Haute-Marne URL.

The immersive qualities of GeoVisionary make the data easier to understand and, although not intended initially, Andra will use GeoVisionary as a communication tool with the local population and with Government as their repository project progresses. Andra consider that this is the easiest way to make their research intelligible to the lay person.

The visualisation incorporates the 3D geological model from GoCAD, which includes lithostratigraphic units, faults etc, topography draped with the colour air photographs, borehole information (including surface and underground (URL) collared boreholes), trajectories, samples etc. Assembling the data in this way has allowed visual identification of locational errors, such as mis-located borehole samples, in the data base permitting the data to be cleaned. While not used for developing the geological interpretation, which is done in GoCAD, it is used for visualising planned developments in the URL.

### 3.4.9 Summary of approaches used and their application

Table 9 summarises the methods used in the Bure site investigation evaluation programme and what they were used for.

Andra have found the geological interpretation that their 3D seismic survey of particular value in understanding their site. They expect that the spatial heterogeneity work that is being undertaken using the 3D seismic data will be very helpful in identifying the best horizon within the Callovo-Oxfordian clay within which to construct the repository galleries. Based on their GoCAD 3D geological model and their digital data repositories they are developing Geovisionary as a tool to both interrogate point data and for the visualisation of their site and proposed repository as part of their public engagement programme.

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Mapping (topographical, geomorphological and geological)** | | Field surveys; topography, geology and geomorphology<br><br>Mapping by BRGM IN 1960s was reviewed and updated by Andra, surveying outcropping formations at local and regional scale and collecting samples | Used to build conceptual model of geology and determine the main features of the geological environment. |
| **Nature, distribution and properties of the sedimentary rock succession** | **Geometry and geological structure** | Geological information from boreholes;<br>From 27 deep boreholes drilled since 1994 | Borehole logging is used to assess the geometry and structure of geological formations. |
| | | Borehole logging<br><br>Data from 68 boreholes previously drilled for oil and gas exploration | Borehole logging is used to assess the geometry and structure of geological formations. |
| | | 3D seismic reflection survey – area of 37km$^2$ in 2010 | Data can be interpreted to;<br>- Determine geometry of the host rock and overlying formations (depth, thickness)<br>- Provide a qualitative and quantitative assessment of lithological variability at the resolution of the future underground installations (~10 m precision). |
| | **Lithostratigraphy and lithological variability** | Layer survey in shafts – detailed measurements taken from an in-situ survey of the host medium; from sinking of shafts and construction of experimental drifts at the URL site. | Combined with 2D geophysical profiles these confirm stratigraphy and feed into the conceptual model of the site.<br><br>Information on the stratigraphy and lithology of the rock formations encountered is recorded. |
| | | 3D seismic reflection survey – area of 37km$^2$ in 2010<br>Including 19 boreholes and associated logs to characterise the stratigraphy. | Determines geometry of the host rock and overlying formations (depth, thickness)<br>Provides a qualitative and quantitative assessment of lithological variability at the resolution of the future underground installations (~10 m precision). |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Nature, distribution and properties of the sedimentary rock succession** | **Lateral continuity and thickness of the formations** | Initial 2D seismic reflection survey. Part of early stage investigations taken in 1994/96. | Regional seismic profiles allow the arrangement of geological layers to be determined; lateral continuity and thickness of the formations. |
| | **Mineralogical characterisation of the host rock(s)** | Mineralogical characterisation of the clay, using samples from excavation shafts and drifts;<br>- permeability testing<br>- electron microscopy<br>- tomography methods | Determination of properties of the clay<br>- permeability (low )<br>- mineralogy of the argillite<br>Used for modelling and characterisation of the host rock. |
| **Geological structure** | **Interpretation of structural domains from discontinuity data** | 3D seismic reflection survey made in 1999 of a 4km$^2$ area in order to site URL. | Survey results were able to show that there are no structural disturbances in the Callavo-Oxfordian argillite (COx) in the study area, making it suitable for siting of the URL. |
| | | 1300km of additional seismic lines from the oil industry were acquired | Additional data which can be used to build on the structural geological model of the region. |
| | **Fault locations** | 3D seismic reflection survey, 1999. Detailed survey parameters allow determination of fault structures. Fault displacements down to 2m are resolved. | The presence of faults is detected and is input into a calculation of confinement capacity.<br>Determination of fault location. |
| | | Information from boreholes;<br>27 deep boreholes drilled since 1994. | The presence of faults is detected and is input into a calculation of confinement capacity. |
| | | 3D seismic reflection survey – area of 37km$^2$ in 2010<br>Including 19 boreholes and associated logs | Used to identify fault locations. Processed data feeds into 3D geological model, which allows determination of confinement capacity (where the absence of faults is desirable) |
| | | 2d seismic reflection survey undertaken in 2006/7. A total of 174 km of survey lines were made for the areas of Fosse de Gondrecourt, the Fosse de la Marne and the Fosse de Joinville grabens and associated faulting which bound the Transposition Zone | Regional seismic profiles were acquired to give detail on the COx and major and minor faults in the area, in order to assess the confinement capacity of the host formation. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Tectonics** | | Seismic monitoring; a network of earthquake recording stations was set up in 30km$^2$ area around the URL. | To monitor earthquakes and assess tectonic activity relative to nearby deformation zones e.g. Alps, Rhine graben, to ensure siting is in an area of low deformation |
| | | In situ stress measurements taken in boreholes | Determination of the natural stress field in the geological formation. Combined with knowledge of structural geology, these data are used for detailed geological modelling, to determine long term affects on topography associated with deformation and uplift/subsidence. This assists the assessment of long-term stability, and geodynamic evolution of the area |
| **Spatial heterogeneity** | | Aeromagnetic survey | Additional data feeds into geological model of the area |
| | | Micro-gravity survey around Meurse/Haute-Marne. | Additional data feeds into the geological model of the area |
| **Geomechanical properties of the host rock** | **Assessment of deformation characteristics and long term monitoring of deformation** | Sensors in experimental drifts (490m depth) and boreholes for measurements and long term monitoring;<br>- vibrating cord extensometers<br>- vertical pendulums<br>- multi-sensor extensometers<br>- interstitial pressure cells, acoustic recording by geophone or accelerometer<br>- vibrating cord interstitial pressure cells<br>- dew-point hygrometers | Sensors are used<br>- to monitor deformations, mechanical displacements and strains, including creep processes<br>-to assess the evolution of the damaged zone around excavations; affects on pressure of the interstitial water and flow rates<br>-to monitor relative humidity, temperature, concentration of toxic gas, corrosion and contamination<br>These measurements are for monitoring and modelling of phenomena affecting the hydraulic, thermal, chemical, and mechanical evolution of the repository and surrounding rocks |
| | **Geotechnical/ engineering properties** | Over 30000 samples from boreholes, experimental drifts and shafts were tested for a range of geomechanical properties | Geomechnical testing provides understanding of confinement properties. Key geomechanical properties provide input parameters for performance assessment and modelling. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Geomechanical properties of the host rock** | **Geotechnical/ engineering properties** | Assessment of geotechnical quality of the host rock; determination of mechanical strength and thermal conductivity | Assesses the properties of the host rock to withstand excavation without fracturing and ability of the formation to dissipate heat associated with decay of the radioactive waste.<br><br>Interaction between formation and engineering materials.<br><br>Analysis of creep behaviour; argillites are stiff, deform little and slowly |
| | | In situ geotechnical measurements<br>- mechanical disturbance monitoring<br>- wall deformation measurements in experimental drifts | Allows damage made to the formation during construction/excavation to be assessed. |
| | | Performance tests on grooves filled with swelling clay sited in experimental drifts | Confirms and evaluates the ability of clay material to self seal fractures. This helps assess the confinement capacity of the geological barrier |
| **Hydrogeology** | **Hydrogeological monitoring,** | Long term monitoring of soil, surface waters etc for environmental studies. | Used for assessment of hydrological properties and long term behaviour. |
| | **Hydrology of the geological formations** | Hydrological measurements taken within shafts at the URL, including water collection and flow rate measurements on the limestones overlying the Callavo-Oxfordian formation. | Calculation of water flow velocities.<br><br>Used for assessment of hydrological properties and long term behaviour.<br><br>Allow calculation and modelling of the likely dispersion pathways of radionuclides through the formations studied. |
| | | In situ permeability measurements of wall rocks surrounding excavations | Excavation effects on groundwater flow pathways can be assessed and modelled. |
| | | Hydrogeological testing from boreholes and springs;<br>- measurement of head gradients<br>- groundwater flow | Assessment of hydrological characteristics of the geological formations, water quality and determination of water resources.<br><br>Hydrological measurements such as hydraulic gradients, permeability, flow pathways allow calculation and modelling of the likely dispersion pathways of radionuclides. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Hydrogeology** | **Hydrology of the geological formations** | Hydraulic head measurements in experimental drifts | Assessment of hydrological properties – groundwater flow in surrounding layers is found to be slow. |
| | | Measurements from borehole geophysics; porosity, density, measurement of hydraulic head | Determination of important parameters to understand the hydrogeological properties of the rock, and feed into quantitative geological model |
| | | Groundwater permeability measurements in experimental drifts | Determination of permeability and water flow properties, in the argillite. These feed into the hydrogeological model. |
| | **Geochemistry of groundwater** | Geochemical analysis of groundwater | Assessment of hydrological characteristics of the geological formations, water quality and determination of water resources.<br>Analysis of speciation, solubility and retention of the radionuclides within the containment facility |
| | | Additional geochemical analyses of fluids encountered in experimental drifts | Analysis of speciation, solubility and retention of the radionuclides within the containment facility |
| **Radionuclide diffusion potential** | **Mineralogical characterization of the host rock** | Mineralogical characterisation of the clay, using samples from excavation shafts and drifts;<br>- permeability testing<br>- electron microscopy<br>- tomography methods | Determination of properties of the clay which will affect radionuclide absorption and diffusion;<br>- permeability (low )<br>- mineralogy of the argillite<br>- nuclide absorption capabilities |
| | **Groundwater flow pathways** | Hydrological measurements taken within shafts at the URL, including water collection and flow rate measurements on the limestones overlying the Callavo-Oxfordian formation. | Allows calculation of water flow velocities, which feed into calculations of the long term radionuclide diffusion in the Callavo-Oxfordian formation. |
| | **Geochemical properties of the groundwater** | Determination of likely chemical interactions between the host rock and groundwater | Analysis of speciation, solubility and retention of the radionuclides within the containment facility, allows interpretation of radionuclide diffusion potential. |
| | **Radionuclide diffusion experiments and measurements** | In situ diffusion tests in the rock laboratory; hydrodynamic tests and modelling allow diffusion parameters to be determined. | Parameters used in model of long term radionuclide diffusion in the Callavo-Oxfordian formation |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Radionuclide diffusion potential** | **Radionuclide diffusion experiments and measurements** | Permeability and diffusion measurements for groundwater and radioactive substances, in experimental drifts | Determination of permeability, water flow properties, and properties of absorption in the argillite. These feed into the hydrogeological model. |
| | **Absorption properties of clay host formation** | Absorption properties of Smectite clays. | Migration of radionuclides affected by clay absorption processes and solubilities in groundwaters |
| | **Thermal conductivity and effect of higher temperature** | Thermal conductivity in the host rock – measured by temperature sensors in experimental drifts and boreholes | Measurements are for used for monitoring and modelling of phenomena affecting the thermal evolution of the repository and surrounding rocks<br><br>Combined with other data, this allows modelling of speciation, solubility and retention of the radionuclides within the containment facility at higher temperatures (thermodynamic and experimental devices are used in a mechanistic approach). |
| **Long term stability of the engineered barrier** | **Experiments in underground laboratory** | Experiments on interactions between construction materials and clay | Provides parameters for geochemical interactions/mineralogical transformations in the disposal cell to be modelled. |
| | | Corrosion of carbon steel in an anoxic environment | Used to assess the behaviour of the waste packages and the matrices in repository conditions (concerning the release of the radionuclides and chemical toxics) |
| | | Performance tests on grooves filled with swelling clay sited in experimental drifts | Confirms and evaluates the ability of clay material to self seal fractures. This helps assess the confinement capacity of the geological barrier. |
| | **Long-term monitoring** | Sensors in experimental drifts for long-term monitoring;<br><br>Hydrogen detector, ultrasonic measurements, sampling, mass spectrometry for radioactive contamination. | Sensors are used<br><br>- to monitor deformations, mechanical displacements and strains, including creep processes<br><br>-to assess the evolution of the damaged zone around excavations; affects on pressure of the interstitial water and flow rates<br><br>-to monitor relative humidity, temperature, concentration of toxic gas, corrosion and contamination |

**Table 9** Summary of data collected from hydrogeological, geophysical, and geological investigation techniques with an explanation of their use for characterisation of the Bure site, including a summary of relevant experiments, monitoring and testing activities at the Meurse/Haute-Marne underground laboratory which are useful for modelling purposes. Summarised from Andra 2005a; *Dossier Argile – Synthesis*

## 3.5 THE NAGRA OPALINUS CLAY EXAMPLE

### 3.5.1 Introduction

In 1985 Project Gewähr, (a "feasibility study") which outlined the *Entsorgungsnachweis* for deep geological storage was submitted to the Federal Council for approval. Findings from Project Gewähr were published in German as a series of Technical Reports (Nagra 1985a, NGB 85-01 – NGB 85-08), which are summarised in English in Nagra 1985b, NGB 85-09. The project detailed the demonstrations of siting feasibility, construction feasibility and long-term safety. This envisioned that a HLW/ILW repository would be sited within the crystalline basement, and an I/LLW repository within the marl formations of the Helveticum, but did not identify potential repository locations. Project Gewähr was reviewed, but the subsequent Federal Government decision which followed in 1988 was that the demonstration of siting feasibility was not met. Geological characterisation of the crystalline basement that was carried out for project Gewähr was synthesised and published in 1994 (Nagra 1994a, NTB 93-09E). The Nagra crystalline work programme is not considered further in this report.

At the request of the federal council in 1988, the search for a suitable site for a deep geological repository was extended to include the sedimentary rock sequences of Northern Switzerland. This has now become the favoured option for disposal. Phase 1 and 2 investigations have been carried out on the sedimentary rocks of Northern Switzerland, and six areas that offer potential for deep geological disposal of radioactive waste have been identified (see section 2.7 above for the six siting regions identified by this work). This completed stage 1 of the sectoral plan.

While waiting for Government approval to proceed, in 2011 Nagra took the opportunity to acquire information from a deep borehole drilled at Schlattingen (near Dissenhofen) for a geothermal heating scheme by logging and sampling the Opalinus Clay.

Further phase 3 fieldwork is proposed to begin in c. 2013 which will consist of new 3D seismic reflection surveys, borehole drilling, core logging and testing, and geological mapping within the siting regions (Nagra 2009, NTB 09-06).

Once these phase 3 site investigations are completed, the surveys should provide sufficient detail to make a final site selection and submit a licence application for geological repository/repositories in 2015 (completing stages 2 and 3 of the sectoral plan). This will then be submitted to the relevant Federal Council, and, assuming that their review is positive and that approval is given, it is envisaged that a HLW/ILW repository will be operational from 2040 and a L/ILW repository from 2030.

Most of the reports by Nagra are published in German, sometimes with an English summary, which has limited the information available for this review.

### 3.5.2 Mapping (topographical, geomorphological and geological)

The first objective was to use data available from Swiss Topo (the Swiss geological survey) as the basis for an initial assessment of each target rock type. Where necessary this was then supported by more detailed fieldwork by Nagra within specific areas of interest.

### 3.5.3 Sedimentary rocks - nature, distribution and properties

A stage 1 geological assessment was first made for the Mesozoic sedimentary rocks of Northern Switzerland (Nagra, 1988, NTB 88-25). The whole sedimentary succession overlying the crystalline basement was examined for potential.

Potential host rocks were assessed with the aim of having a basis for the following favourable characteristics:

- Stable tectonic conditions and predictability of structural geology;
- Sufficient depth of the host rock (for engineering and safety case considerations);
- Sufficient properties and thickness of the host unit/formation;
- Favourable hydrogeological conditions and predictability;
- Favourable seismicity, neotectonic conditions and predictability of long term changes.

As such, an initial assessment of the sedimentary succession for potential storage options was outlined in Nagra 1988, NTB 88-25, which narrowed down the options to identify the Opalinus Clay, Brauner Dogger and Effingen Beds/Member, and Helvetic Marl as potential host sedimentary units for a deep geological repository.

2D regional seismic investigations, carried out in 1991/92, supplemented the regional survey that had already taken place in North Switzerland to characterise the crystalline basement. (Nagra, 2000a, NTB 00-03). Interpretation of these surveys showed that the in north of Canton Zürich, the Opalinus Clay had experienced minimal tectonic stress. It was therefore possible to identify an almost undisturbed area of 50 $Km^2$ in the Zürcher Weinland, as the area of greatest potential to site a deep storage facility because it is likely to have minimal structural complexity. (Nagra 1994d, NTB 94-10)

To achieve better constraints on the geology of the Opalinus Clay in the Zürcher Weinland, a 3D seismic survey was carried out in 1997, in order to characterise the potential host rock in more detail for its potential to host a geological repository for high level waste. (Nagra 2000a, NTB 00-03). The three dimensional reflection seismic survey along with the data from the Benken borehole which was drilled in 1998/99 give a good base of evidence with which to assess the stratigraphy of the investigation area. The high resolution seismic surveys show detail of geological structures on a metre scale. Structural analysis was carried out using conventional amplitude displays in profile sections, and it has been possible to determine and resolve faults and flexures with a vertical displacement of down to 10m with ease. Coherence data and seismic attribute maps can be used to constrain even smaller structures than this. (Nagra 2000a, NTB 00-03).

In addition to the 3D seismic survey, phase 2 characterisation included the sinking of the Benken borehole, in the Zürcher Weinland in 1998/99. Stratigraphy, as well as sonic and density logging geophysics measurements from the borehole could be correlated with the seismic refection survey (Nagra 2000b).

In 2002 the *Entsorgungsnachweis* for Nagra’s Opalinus Clay project was delivered. (Nagra 2002c, NTB 02-05) The Opalinus Clay project aims to demonstrate siting feasibility within the

Opalinus Clay geological formation in the Zürcher Weinland. The Opalinus Clay occurs 400 to 750 metres below the surface, and is 110 – 120m thick stratigraphically. This was under review by the Federal Council who have now (1st December 2011) given approval for siting studies to commence in three areas. As a result of this approval further 3D seismic studies for the potential Bözberg, Nördlich Lägeren, Jura-Südfuss, and Südranden sites may be undertaken, as well as underground characterisation studies (phase 3) in preparation for siting a deep geological repository/repositories.

The 3D survey was tied to a single borehole using a synthetic seismogram and walk-away VSP techniques. The investigators found that the data had a high spatial resolution, allowing them to map features down to metre scale (Birkhäuser et al, 2001). The seismic interpretation involved structural analysis using conventional amplitude displays to directly map faults with throws down to 10 m. Seismic attributes including coherency were used to map smaller structures. Various seismic attributes were also extracted in the vicinity of the borehole and related to lithostratigraphic units. The resulting attribute maps provided qualitative information on the nature of the host rock throughout the rest of the 3D survey.

The data are held within a GIS, to allow spatial interpretation and 3D modelling packages are used (Nagra 2000a) to develop understanding of the geological structure of the possible siting regions. Interpretation of the data has allowed Nagra to identify six areas that will be evaluated further for siting an ILW/LLW repository three of which will also be evaluated for their suitability for hosting a HLW/ILW repository.

### 3.5.4 Spatial heterogeneity

Seismic attributes including coherency were used with the aim of mapping smaller structures. Various seismic attributes were also extracted in the vicinity of boreholes and related to lithostratigraphic units. The resulting attribute maps provided qualitative information on the nature of the host rock throughout the rest of the 3D survey areas.

Understanding of the spatial conditions is currently largely based on 2D seismic investigations and the results from deep boreholes. The siting regions are located in a region that has partly been tectonically overprinted by the folding of the Jura Mountains (precursory folding zone). For this reason, the host rock has areas with largely ‘quiet’ bedding as well as zones with increased tectonic dissection.

### 3.5.5 Geological Evolution

The three siting regions with the Opalinus Clay potential host rock – Zürich Nordost, North of Lägern and Jura Ost – are characterised by a simple and stable geology with gentle folding and some faulting.

Seismotectonics is used to analyse recent tectonic processes in the crust, and provide useful information on the location of active fracture zones and in-situ stresses. The Swiss Seismological service operates a network of measurement stations in the Northern Switzerland area set up in 1983 for this purpose. (Nagra 1988, NTB 88-25) Data from the seismic stations has been interpreted to suggest that a relatively constant stress field is present in Northern Switzerland, with the main horizontal stress field aligned broadly NW-SE.

### 3.5.6 Summary of approaches used and their application

Table 10 summarises the methods used in the Nagra evaluation programme and what they were used for.

Nagra consider that the information gained from 3D seismic surveys allowing the development of the geological interpretation of a site area is an important tool in their geological investigation.

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Mapping (topographical, geomorphological and geological)** | | Geological mapping<br>- mapping of region Kaisten-Zurzach,<br>- map compilation for northern Switzerland<br>- outcrop mapping of the Black Forest | Determination of the main features of the geological environment<br>Assessment of geological complexity and suitability of potential host rock formations<br>Use to create structural geological and conceptual model of the crystalline basement<br>Feeds into the site descriptive / geological model, used for assessment of safety relevant properties and predictions of long term behaviour. |
| **Nature, distribution and properties of the sedimentary rock succession** | **Geological structure and stratigraphy** | Deep boreholes<br>- core logging | Borehole logging;<br>- helps determine depth of host formations, rock mechanical stability<br>- can be correlated with seismic reflection surveys, to give a detailed characterisation of the host rock |
| | | Refraction seismics | Analysis and measurement of bedrock structure |
| | | Aeromagnetics | Additional data to aid geological mapping and determination of geological structure |
| | | Gravimetry | Additional information on deep subsurface geology |
| | | 3D seismic reflection survey<br>tied to a single borehole using synthetic seismogram and walk-away VSP data. | Results in high quality imaging of the rock strata, allowing detailed characterisation of the host rock. this feeds into the geological model, detailed site descriptive model and predictions of the geological evolution of the area |
| **Nature, distribution and properties of the sedimentary rock succession** | **Geological structure and stratigraphy** | Borehole geophysical logging<br>- sonic and density measurements as well as core logging. | These data correlate with 3d seismic reflection profiles, in order to ensure robust geological modelling |
| | **Lateral continuity and thickness of the formations** | 2D seismic reflection surveys; initial regional surveys | Depth, thickness and lateral extent of the host formations. Used to identify favourable areas for further study, based on measurements of structural complexity and minimal tectonic stress.<br>These data feed into the conceptual geological model and detailed site descriptive model |
| | **Mineralogical characteris-ation of the host rock(s)** | Core samples from deep boreholes | Sample analysis gives important details and parameters for modelling;<br>- mineralogy and chemistry of rock samples<br>These data are used to develop and refine the geological model. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Structural geology - fault locations and behaviour** | | Deep boreholes<br>- detection of structural features, faults, fractures etc. | Used in order to identify suitable repository sites away from deformation zones and fractures<br>Also used to develop and refine the geological model. |
| | | 2D seismic reflection surveys; initial regional surveys | Identification of water conducting features; faults, fractures etc in the crystalline basement, including the Permo-Carboniferous Trough of Northern Switzerland<br>These data feed into the conceptual geological model and detailed site descriptive model |
| | | 3D seismic reflection survey<br>Tied to a single borehole using synthetic seismogram and walk-away VSP data. | Determination of structural complexity; detects the presence of faults, fractures and displacements, in order to site repository away from deformation zones |
| **Tectonics** | | Neotectonics<br>- tectonic studies<br>- microseismics measurement network<br>- geodesic measurements<br>- geomorphology studies<br>- stress measurements | Assessment of tectonic stability, uplift and erosion rates, and to identify areas of low tectonic stress.<br>Seismotectonics locates active fracture zones by measuring stress, and assess the regional stress field for predictions of geological evolution. |
| **Spatial heterogeneity** | | Hydrogeological measurements; including hydraulic packer tests, and fluid logging (electrical conductivity and temperature measurements) in boreholes | An upper high permeability domain overlying a low-permeability domain was identified in the crystalline basement |
| **Geomechanical and geothermal properties of the host rock** | **Deformation characteristics** | Measurements from deep boreholes<br>- rock mechanics measurements<br>- borehole logging helps determine rock mechanical stability | Rock mechanical properties can be assessed – fracture density, fracture healing, deformation mode, occurrence of shear zones, stability. |
| | **Geotechnical/ engineering properties** | Analyisis of core samples from deep boreholes | Host rock properties; determination of permeability, rock density, thermal conductivity, heat capacity, Vp velocity,<br>These are used to develop and refine the geological model. |
| | | Geotechnical and geomechanical testing of the Opalinus clay | Assessment of geomechanical properties; cyclic deformations, fracture generation mechanisms, ability of Opalinus clay to self seal fractures |
| **Hydrogeology** | **Hydrogeological monitoring,** | Long-term monitoring of 7 mineral/thermal springs and wells | Outflow locations, dilution, hydrogeology. |
| | **Hydrology of the geological formations** | Hydrogeological measurements; including hydraulic packer tests, and fluid logging (electrical conductivity and temperature measurements) in boreholes | Determines permeability of the host rock and surrounding units, and water flux and flow rates though the host rock.<br>These factors feed into a hydrogeological model |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Hydrogeology** | **Hydrology of the geological formations** | Hydrochemical sampling of over 100 springs and wells | Information used to give insights into groundwater flow paths |
| | **Geochemistry of groundwater** | Hydrochemistry; Water sampling in boreholes and analysis. | Determines chemical properties of the groundwater (aggressivity, redox potentials etc.) |
| **Radionuclide diffusion potential** | **Properties of the host rock** | Radionuclide diffusion and retention, determination of stress, migration of gases. | Assessment of processes and mechanisms in undisturbed Opalinus clay affecting radionuclide diffusion. |
| | **Groundwater flow pathways** | Hydrogeological measurements; including hydraulic packer tests, and fluid logging (electrical conductivity and temperature measurements) in boreholes | Tests provide water flux and flow rates though the host rock. Information on groundwater flow pathways assist assessment of radionuclide transport properties and paths. |
| | **Radionuclide diffusion experiments and measurements** | Results of geochemical analysis of groundwater samples from boreholes | Used to determine radionuclide solubilities within groundwaters and their affect on radionuclide diffusion |
| | | Measurement of radionuclide diffusion parameters for the engineered and geological barriers | In order to model radionuclide diffusion processes; interactions between waste, engineered and geological barriers. |
| | **Adsorption properties of clay host formation** | Radionuclide diffusion studies | Measurement of nuclide retention in the host rock, due to adsorption on clay minerals and low permeability of the host rock. |
| **Long term stability of the engineered barrier** | **Engineering project studies** | Testing of construction methods and operating procedures for the facility | Design and analysis of appropriate engineered barriers and facilities Performance assessment of the waste containers, engineered and geological barriers, and construction methods and materials |
| | | Hydrological testing of rock and construction materials | Hydrogeological and geological characterisation of water conducting features such as fractures etc associated with the engineered/geological barrier interaction– related to long term diffusion of radionuclides |

**Table 10** Summary of data collected from hydrogeological, hydrochemical, geophysical, and geological investigation techniques as well as testing in underground rock laboratories and other research facilities employed by Nagra in order to achieve a siting proposal and a site descriptive model for a potential repository site.

## 3.6 THE BGR GORLEBEN EXAMPLE

The Federal State of Lower Saxony selected the Gorleben Salt Dome as a possible repository for the final disposal of radioactive waste in 1979. The objectives of the geological investigations were to:

- Assess the suitability of the site and
- Demonstrate safe construction and operation of the proposed facility and its long-term safety.

The geological and hydrogeological characteristics of the area were investigated from the surface and underground. Data were used to investigate a number of forward scenarios, such as subrosion (erosion of the rising salt dome over time); diapirism and the formation of glacial channels in the upper surface of the salt dome.

The Mesozoic sedimentary rocks and Quaternary deposits overlying and adjacent to the salt dome are referred to as 'overburden'. The objectives of the investigation were to carry out geological (straigraphical and lithological), structural-geological, hydrogeological/hydrological investigations of both the salt dome and the 'overburden'.

Most reports on the Goreleben site investigations are not freely available and many of those that are have only been published in German which has limited the access to information on this program.

### 3.6.1 Mapping (topographical, geomorphological and geological)

The focus of the exploration was to gain detailed knowledge of the extent and thickness of the overburden and salt dome beds and their hydraulic parameters (grain-size, permeability, porosity etc.) based on sample analyses and borehole logs.

Prior to drilling of the site pre-existing geological maps at 1:25 000 and 1:200 000 scales were consulted. In the Gorleben area deep boreholes had previously been drilled for local water supply (up to 200 m depth) or prospecting for salt (potash) and oil. Four deep boreholes were drilled in the early part of the 20$^{th}$ century. Seismic reflection surveys from 1947 onwards arising from hydrocarbon exploration were followed up by several deep boreholes and an outline salt dome map was produced (Jaritz, 1973). Hydrocarbon investigations (1950s-1960s) indentified the adjacent Rambow salt dome and its adjoining rim synclines. These precursor regional studies helped to guide the detailed investigations at Gorleben.

In order to characterise the Gorleben site, an intensive drilling programme was carried out to characterise the geology (and especially the hydrogeology). An initial wide-mesh exploration programme was followed up by closer spaced boreholes to better understand some of the sub-surface features (e.g. the nature of Quaternary channels in the upper surface of the salt) focussing on the Quaternary geology. The main objectives were to create a geological model of the salt dome, to determine if the salt dome is sufficiently large in area to host a GDF, that it contains neither significant volumes of gas or brines and that secondary minerals, such as carnalite, that affect the behaviour of the salt are not present in significant quantities.

The majority of the exploration boreholes (185), targeted to characterise and model the geology and hydrogeology of the area, reached the base of the Tertiary or Quaternary aquifer system ('overburden') at depths of between 120 m to 440 m below ground level. A further 44 boreholes were sunk to depths of up to 520 m to investigate the salt table (i.e. the surface of the salt body below the gypsiferous cap rock), to investigate the nature of the cap rock and uppermost sections of the salt dome. Of these, 4 deep boreholes were drilled to final depth of ca. 2000 m to characterise the salt body itself, especially the stratigraphy, mineralogical and geochemical composition of the salt, and to model the internal structure of the salt dome, determine the presence of any gas and/or brine occurrences, and to create a geological map/model of the designated exploration level at about 840 m depth.

Critical to an understanding of the geological characteristics, in addition to assessment of the cores and drill cuttings, was systematic recording of geophysical wireline logs (downhole logs). These were carried out in all boreholes except for the shallow Quaternary boreholes in order to correlate between boreholes, characterise the petrology and mineralogy of the rocks and deposits.

In order to better understand the geometry and architecture of the ‘overburden’ and adjacent rocks and their relationships to the salt dome, a number of geophysical surveys (seismic reflection and refraction) were carried out between 1980 and 1997. These comprised 549 deep soundings and 16 seismic reflection profiles, as well as 82 high-resolution seismic profiles with a total length of 312 Km. In addition, a seismographic array was installed to continuously monitor any local earthquake activity in the area from February 1986 onwards. Seismic reflection and refraction techniques were used to determine the structure and boundaries of the salt dome, including the shape of the base of the dome (Zirngast, 1991; Zirngast et al., 2003). The flanks of the salt dome were surveyed using down hole (down borehole) seismic reflection techniques in order to register reflections of the seismic waves generated at the surface.

Further seismic reflection surveys were carried out in the area of the Gorleben salt dome in 1984, supplemented by seismic refraction surveys including undershooting of the salt dome to understand the geometry of the ‘root’ of the structure and underlying rocks. Sixteen seismic reflection surveys were recorded and analysed, totalling 150 Km length. Subsequent high resolution seismic reflection profiles (1994-97) were carried out to identify the structure of the overlying Tertiary and Quaternary sediments, as well as surface of the Gorleben and adjacent Rambow domes. Vertical seismic profiles were surveyed in 42 boreholes to aid interpretation of the shallow seismic investigations.

In summary, the results of the geophysical investigations allowed the BGR to analyse the rim synclines adjacent to the salt domes, identify possible migration paths in the overlying sediment (‘overburden’), and more precisely define the boundaries of the salt dome at depth. The data were integrated into the 3D model of the salt dome.

### 3.6.2 Sedimentary rocks - nature, distribution and properties

Stratigraphical, micropalaeontological and palynological analyses were carried out on the Cretaceous to Quaternary age sediments.

The Tertiary and Quaternary strata overlying the salt dome have a maximum thickness of 439 m, and form a series of aquifers separated by aquitards. Sands and gravels of Tertiary to Elsterian age form the lower aquifer; these are separated from the Saalian and Weichselian age deposits that form the upper aquifer by a low permeability aquitard. The aquitard is locally absent to the north and south of the salt dome so that the aquifers are in hydraulic contact with the regionally important Tertiary Braunkohlensande aquifer. The Elsterian Gorleben channel is the dominant structural feature that influences groundwater flow since it is filled with permeable channel sands that locally overlie the cap rock and Zechstein salt.

### 3.6.3 Superficial (drift) deposits - nature, distribution and properties

In order to better understand the geometry and physical properties of the Quaternary sediments with regard to their hydrogeological properties, the following were undertaken:

- A surface mapping programme in conjunction with a borehole programme and
- A shallow seismic survey to explore the surface of the salt dome and the architecture of the Quaternary channel structures and deposits, and to assess Quaternary to Recent halokinesis (salt doming).

Quaternary deposits (part of the 'overburden') were mapped over the whole area to help characterise the sediments of the Lower Terrace and Holocene at 1:25 000 scale with more detailed coverage of the Hohbeck push-moraine (a ridge of glacial deposits) at 1: 5 000 scale. Techniques included assessment of natural exposures, morphological mapping, petrofabric analysis and augering and drilling shallow boreholes to a minimum depth of 2 m (5300 sites), with additional deeper drillings to penetrate the Holocene deposits. Data from previous wells and geotechnical investigations in the area were incorporated in to the map/model.

As part of the hydrogeological studies (see below) a pedological study was carried out to gather areal data on groundwater recharge rates. Sampling-rod drillings (2300 soundings) and shallow excavations were carried out, supplemented by soil-physical surveys and soil-mechanical laboratory tests resulting in a soil and land-use maps.

The overlying Quaternary sediments were initially deposited in deep sub-parallel channels up to 200 m deep and 40 m in length. In places the underlying Tertiary sediments were completely eroded so that earliest Quaternary deposits rest on the salt cap rock (anhydrite) or directly on the salt. The lower Quaternary sediments include clays, silts, sands and gravels laid down in fluvial (river) or lake environments. The deposits of the Elsterian glaciation (about 450,000 years ago) include sand and till (boulder clay). A later, Saalian glaciation is present over a wider area and include sand, gravel and till often highly contorted by the ice sheet. During the subsequent Weichselian glaciation (about 100,000 years ago) the area was not covered by ice and pro-glacial sand was deposited in river terraces along with aeolian (wind-blown) sand and lacustrine clays. Finally, during the Holocene (11, 500 years ago) fluvial sand, mud and local peat was deposited along with wind-blown sands forming dunes and dune-fields.

The Gorleben Glacial Channel and its permeable sand deposits are of prime importance when assessing the long-term safety of a potential repository at depth within the salt dome because it is direct contact with the Zechstein evaporites and the increase in groundwater salinity at these locations.

### 3.6.4 Geological structure

The in-situ sub-surface exploration commenced with the sinking of the main shafts Gorleben 1 (1986-97) and Gorleben 2 (1989-95) spaced 400 m apart. This continued with a drift excavation for the potential GDF infrastructure at the 840 m depth level on October 4, 1995 (Shaft 1) and November 18, 1995 (Shaft 2) – connection of the shafts via the main drift was completed about a year later on October 21, 1996.

The underground exploration was continued with construction of operational chambers in which a range of exploration and geotechnical measurements were carried out to characterise the complex structures and mineralogy in the various salts.

It has been estimated (Köthe et al., 2007) that 53% of the original 1 400 m thick Zechstein salt in the wider Gorleben area have migrated to the present-day salt dome. Salt flow velocities at the main repository depth (840 m below sea level) were 0.337 mm maximum per year in Late Cretaceous time (uplift of 0.08 mm per year) and up to 0.071 mm per year from the Miocene through to the Quaternary (uplift of 0.02 mm per year).

Detailed mapping and photography of the shaft walls and drifts/cavities was carried out in the sub-surface in order to record every tectonic and sedimentary feature that might provide information on the geological history and dynamics of the salt rock. The mapping scale ranged from 1:25 to 1:100 depending on the level of detail required and the complexity of the geological structures. Mapping results of the curved walls were digitally converted to horizontal projections. Ultraviolet light (fluorescence) was used to map out any hydrocarbons seeps.

### 3.6.5 Mineral deposits

The area has evaporite deposits - salt and potash being the more important minerals from an economic point of view and the area has been evaluated in the past for these resources. The area has also been examined for hydrocarbon resources (and a significant number of boreholes drilled). The authors do not know if and to what extent these have been considered by the programme.

### 3.6.6 Spatial heterogeneity

Electromagnetic reflection surveys (EMR) were carried out in the deep surface exploration boreholes, the underground shafts/cavities and in sub-surface boreholes with the objective of locating the boundaries between different rock types (e.g. halite – anhydrite) and to identify lithostratigraphical horizons and petrophysical heterogeneities.

High-frequency absorption surveys (HFA) were conducted in the surface exploration boreholes to detect anhydrite and/or saliniferous clay as opposed to halite. However, they were discontinued due to the presence of brine inclusions.

### 3.6.7 Geological Evolution

The structural, stratigraphical and sedimentological history of the Gorleben salt dome, and its evolution over geological time, especially from the Tertiary to Quaternary (the last 65 million years), provided scenarios for the prediction of future uplift of the salt dome and potential erosion of its upper surface.

It is interpreted that the salt body first developed as a pillow-like structure and evolved into a mushroom-shaped diapir rising upwards into the higher levels of the overlying Mesozoic sediments. By Early Cretaceous time (ca. 140 million years ago) the top of the salt dome lay at, or near, the surface resulting in erosion of the salt. Rapid uplift of the salt dome continued into early Tertiary times (ca. 60 million years ago) before declining from Tertiary to Quaternary times (up to the last 2.5 million years ago). In late Tertiary times the anhydrite-rich cap rock was subjected to karstification and erosion (Jaritz, 1994). Subsequently, during the Elsterian Glaciation the upper part of the salt dome was further eroded and channels were created in its surface.

Salt migration depends on the overlying beds, regional tectonics and the availability (supply) of an underground salt. Köthe et al. (2007) conclude that because geological conditions will not change significantly in the near future and the remaining amount of salt below the adjoining rock is relatively small, it can be expected that salt migration into the salt dome area will further decline over time. Up to 47 % of the salt originally deposited in the Zechstein basin have risen to the surface and have been eroded away. In the Gorleben-Rambow area 185 $Km^3$ of salt remains, about half of which has accumulated in the salt dome.

Mineralogical and geochemical investigations were carried out to determine the genesis, post deposition alteration and internal stratigraphy and structure of the salt dome (Bornemann et al., 2002). Cores were logged and described in detail, and a photographic record produced. Qualitative mineralogical composition of the evaporite deposits was determined mainly by X-ray diffraction analysis (XRD by geochemical analysis and occasional thin section microscopy). Quantitative mineralogical composition was determined from the chemical components, with the exception of kyanite that was determined using quantitative XRD. ZECHIN-7 software was used to determine the quantitative mineralogical composition (e.g. halite, carnalite, sylvite, anhydrite etc.) of each sample.

The Gorleben area is typified by relatively stable tectonics, especially over the last 500 000 years. Subsidence rates of less than 1 mm per year are typical. In the Late Tertiary and part of the Quaternary the salt dome was eroded to form a shallow depositional basin. Seismic reflection surveys conducted in the 1980’s indicated that there was no evidence of major basement faults beneath the salt domes, as had been postulated earlier, although faults of minor displacement, not imaged on the seismograms, may be present.

### 3.6.8 Summary of approaches used and their application

Table 11 summarises the methods used in the Gorleben evaluation programme and what they were used for.

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Mapping (topographical, geomorphological and geological)** | | Geological exploration activities; examination of published survey maps. | Helps to characterise the composition, thickness and extent of overburden and salt dome beds. |
| | | Geological mapping of the quaternary sediments. Assessment of natural exposures, morphological mapping, petro-fabric analysis, shallow augering. | Analysis of near-subsurface material to provide information to improve understanding of groundwater behaviour and recharge rates. |
| | | Underground geological mapping – undertaken through shaft walls and underground tunnels/mines.<br>Ultraviolet light was used to map any hydrocarbon seeps. | To record information to help understanding of the geological history and dynamics of the rock. |
| **Nature, distribution and properties of the sedimentary rock succession** | **Geometry and geological structure** | Seismic reflection and refraction surveys;<br>549 deep soundings, 16 seismic reflection profiles, 82 high-resolution profiles with total length 312 km. | Used to determine structure and boundaries of the salt dome, particularly the shape at the base of the salt dome. Surveys allow analysis of rim synclines adjacent to salt domes. Data were integrated into 3D model of salt dome. |
| | | Interpretation of logging and samples from 281 boreholes collected between 1979-1998.<br>Borehole logging methods:<br>• natural gamma ( GR log)<br>• self-Potential (SP log)<br>• focussed electric (FEL log)<br>• borehole calliper (Calliper log)<br>• neutron log<br>• sonic log<br>• salinity log<br>• density also logged in majority of boreholes. | Determines the character, composition, thickness and extent of overburden and salt dome beds. |
| **Nature, distribution and properties of sedimentary rock succession** | **Lithostratigraphy and lithological variability** | 158 boreholes for exploration of the salt dome (200-450m depth) | Used to analyse the composition of the overlying overburden strata. |
| | **Mineralogical characterisation of the host rock(s)** | Mineralogical and geochemical investigations of samples, using X-Ray Diffraction (XRD) and thin section microscopy methods. | Determination of mineral composition for selected representative samples. |
| **Geological Structure** | **Fault locations and behaviour** | Fissureometer measurements – at exploration depth | Used to monitor a joint system in order to predict and assess typical behaviour |
| **Tectonics** | **Measurements of regional tectonic situation** | Seismological measurements – Gorleben seismometer network; six borehole stations GOR 1-6 were installed at 300m depth in pentagon distribution. | Allows earthquake hazard to be assessed. Interpretation has indicated that no recent fault displacements close to the salt dome have occurred recently and that it is in a tectonically stable situation. |
| | **Measurements of principal stress at location** | Borehole testing; BGR over-coring method applied in exploration boreholes | BGR over-coring method measures stress release when a core becomes detached from the formation. Part of data suite to measure in-situ rock stress. |
| | | Stationary stress monitoring stations using four pressure cells (hydraulic valve sensors) at each station. Installed in exploration boreholes. | Set up to record and monitor stress changes, allows long term stress field behaviour to be assessed, modelled and monitored. |

| Information requirement | | Method of measurement | Interpretation and modelling method |
|---|---|---|---|
| **Spatial heterogeneity** | | Electromagnetic reflection surveys (EMR)<br>High frequency absorption surveys (HFA) | EMR and HFA surveys detect geoelectrical unconformities within the salt deposit. These help to assess the homogeneity of the salt dome, particularly the presence of rock types other than Halite. These are particularly suitable for salt domes due to their inherent low electrical conductivity. |
| **Geomechanical and geothermal properties of the host rock** | **Deformation characteristics** | Convergence measurement instruments combined with extensometer and inclinometer measurement chains were set up in exploration horizons connected to shafts Gorleben 1 and Gorleben 2.<br>Horizons were set up at various different depths at exploration level (350 – 770 m below sea level) in the salt rock. | Convergence measurement profiles were produced<br>Rock mass deformations and stress changes around the shafts were measured as comprehensively as possible.<br>This will help to monitor short-term and long-term stress changes and allow model based calculations on the stress field. |
| | | Salt dome geothermy; modelling of temperature field based on standard values was verified by temperature measurements from boreholes.<br>Temperature logging; temperature is measured at almost every measuring point during geomechanical and monitoring measurements. | Corrected temperature values are used to calculate formation temperature at exploration level and vertical heat flow values.<br>Combined with analysis and testing on samples thermal expansion coefficients for heat changes, these data are used to determine and model the natural 3D temperature field within the salt dome, and assess how it is affected by exploration and subsequent operations. |
| | **Geotechnical/ engineering properties** | Uniaxial, biaxial and triaxial pressure tests on samples representative of the host salt dome | Used to assess the thermo-mechanical properties and material parameters of the rocks at site. These parameters are used to develop a material model description of the thermo-mechanical rock mass behaviour. |
| | | Brazilian tests | Used to calculate tensile strength |
| | | Creep tests | Creep tests under low uniaxial pressure are used to analyse creep behaviour, and dilatant deformation properties. These provide input into a numerical model for long term deformation behaviour of the salt dome |
| | | Ultrasonic tests | To assess sample quality – anisotropy associated with layering or crystal alignment – modulus of elasticity, Poisson's ratio |
| | **Prediction and modelling of long term behaviour** | Lab based testing provides accurate input parameters for important geomechanical properties (e.g. density, dynamic modulus of elasticity and Poisson's ratio) | These parameters are input into numerical models which simulate the load bearing behaviour of the exploration mine and geological barriers as well as predict temporal and spatial stress changes. |
| **Hydrogeology** | **Hydrogeological monitoring,** | 320 near-surface groundwater exploration wells | To monitor water table levels. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Hydrogeology** | **Hydrology of the geological formations** | In-situ permeability measurements in 158 exploration boreholes (200-450m depth) using double packer tests.<br>Borehole tools penetrate and characterise any isolated pockets of fluid within the salt dome using outflow pressure measurements. | Investigation of the hydrogeology of the salt dome provides input parameters for 3D groundwater flow model. |
| | | Surface and near surface testing:<br>- water pumping tests<br>- soil mapping to determine percolation and recharge rates<br>- permeability tests of drill cores<br>- sorption tests of sediments | Determination of hydrogeological properties of the overburden, which provide input parameters for a 3D groundwater flow model. |
| | | Geo-electrical ground survey | To identify freshwater/saltwater interface; input into groundwater flow model. |
| | | Seismic reflection and refraction surveys;<br>549 deep soundings, 16 seismic reflection profiles, 82 high-resolution profiles with total length 312 km. | Allows possible migration paths in the overburden to be evaluated. |
| | | Borehole logging and samples from 281 boreholes collected between 1979-1998.<br>Borehole logging methods:<br>• natural gamma radiation ( GR log)<br>• self-Potential (SP log)<br>• focussed electric (FEL log)<br>• borehole calliper (Calliper log)<br>• neutron log<br>• sonic log<br>• salinity log<br>• density also logged in majority of boreholes. | Determines the composition, thickness and extent of overburden and salt dome beds.<br>Neutron logging was used to determine porosity in selected boreholes.<br>These factors provide input into hydrogeological calculation models for large scale groundwater movement. |
| | | Permeability tests | Hydraulic borehole tests determine the permeability of the rock in-situ. |
| | | Geological mapping of the quaternary sediments.<br>Assessment of natural exposures, morphological mapping, petrofabric analysis, augering near subsurface. | Analysis of near-subsurface material to provide information to improve understanding of groundwater behaviour and recharge rates. |
| | **Geochemistry of groundwater** | 320 near-surface groundwater exploration wells | Extraction of water samples for analysis |

**Table 11** Summary of data collected from in-situ and lab-based geomechanical testing methods, as well as hydrogeological, geophysical, geothermal, and geological exploration activities with an explanation of their use for characterisation of the Gorleben site. Summarised from Bornemann et al., 2008 and Bräuer et al., 2011.

## 3.7 THE DOE WIPP EXAMPLE

The WIPP underground repository is certified by the US Environmental Protection Agency for the storage of transuranic radioactive waste. Following about 25 years of study and evaluation the first waste arrived in March, 1999. Radioactive waste is placed in underground caverns within bedded halite (rock salt - sodium chloride) at a depth of about 655 m below the ground surface.

This overview is based on the in Final WIPP Supplemental Environmental Impact Statement (SEIS-II) document (DOE, 1997b and references therein) with additional information from: Powers et al., 1978; Lappin and Hunter, 1989; Borns, 1997; Kuhlman and Barnhart, 2011.

The WIPP site is located about 30 miles east of Carlsbad in southeastern New Mexico, in the Pecos Valley Section of the Great Plains Physiographic Province. Geologically, it forms part of the Delaware Sub-basin of the Permian Salt Basin, which extends over part of 5 states.

The investigations since 1990 have had a largely hydrogeological objective focussing on extensive hydrogeological testing and brine characterisation.

### 3.7.1 Mapping (topographical, geomorphological and geological)

The ground surface of the site slopes gently from east to west, from an elevation of 1,088 meters (3,570 feet) above sea level at its eastern boundary to 990 meters (3,250 feet) above sea level along its western boundary. The area is characterised by a high plains desert environment. The terrain throughout the province varies from plains and lowlands to rugged canyons. Because of the seasonal nature of the rainfall, most surface drainage is intermittent. The Pecos River, 20 kilometres southwest of the WIPP boundary, is a perennial river and the main drainage for the region. A natural drainage divide lies between the Pecos River and WIPP. As a result, the Pecos drainage system does not currently affect the site. Local physiographic features include Nash Draw and the San Simon Swale.

### 3.7.2 Sedimentary rocks - nature, distribution and properties

Geologically the WIPP site it is located in the northern part of the Delaware Sub-Basin, a structural basin underlying present-day southeastern New Mexico and western Texas and containing a thick sequence of sandstones, shales, carbonates, and evaporites (salts) of Permian age, and capped by Triassic rocks.

The repository depth is about 655 m below ground surface in evaporite (salt) rocks of Permian age, within the Salado Formation. The upper Permian succession is thickest in the northern part of the Delaware Sub-Basin where it comprises in upwards sequence the Castile, Salado, Rustler and Dewey Lake Formations. The WIPP repository is located, at depth, in the lower part of the Salado Formation. The Castile Formation is underlain by the Bell Canyon Formation.

The subsurface geology at WIPP was investigated and monitored using a variety of geophysical methods including the seismic, electrical, electromagnetic and potential field techniques (magnetic profiling and microgravity profiling) (Borns, 1997). The objective of the geophysical studies was to provide an understanding of:

- The nature of site deformation;
- Local and regional tectonics: and
- Site stability.

Geophysical methods were used to delineate possible brine reservoirs beneath the repository and have helped define the disturbed rock zone associated with underground excavations. The role of geophysics at the WIPP site evolved during the investigations. Early uses, from 1975 onwards, were characterisation of the site to satisfy site selection criteria. Later, from the 1980's, the geophysical program supported experimental and field programmes such determining the hydrogeology of the Saledo Formation and underground rooms and vaults excavated in the salt rock.

### 3.7.3 Superficial (drift) deposits - nature, distribution and properties

The area has relatively thin superficial deposits and has not been glaciated. In the immediate vicinity of WIPP, numerous small mounds formed by wind-blown sand characterize the land surface. A layer enriched in calcium carbonate material (caliche or calcrete), known as the Mescalero caliche, is typically present beneath this surface layer of sand. This Quaternary-age caliche, known locally as the Gatuña Formation, ranges in age from about 510,000 years at the base of the layer to about 410,000 years in the upper part, based on samples within the layer. The caliche layer overlies a 600,000-year old volcanic ash layer that has been radiometrically dated. The Mescalero caliche can be found over large portions of the Pecos River drainage area and is generally considered to be an indicator of surface stability.

### 3.7.4 Geological structure

Geophysical studies were used in the early characterisation of the site to determine the continuity and predictability of strata, thickness of the salt, extent of any dissolution, deformation (e.g. faults, salt tectonics) and seismicity. Seismic reflection studies revealed both continuity and thickness of the salt formation, absence of salt dissolution, that there was no evidence for Quaternary or later faulting, and that the seismic risk was low. Electrical profiling indicated an absence of dissolution breccia pipes (often associated with salt deposits).

### 3.7.5 Mineral deposits

While the salt deposits which host the repository are at a depth where exploitation for salt is unlikely, they may offer potential for gas storage and similar purposes. The area is close to exploited hydrocarbon resources.

### 3.7.6 Tectonics

Regional seismicity is related to 2 main earthquake clusters associated with the Rio Grande Rift located to the southwest of the site and the Central Basin Platform to the *east* of the site so the objective of the tectonic studies was to:

- Determine the history of tectonic activity; and
- Determine seismic risk.

The upper magnitude limit for the WIPP site was set 4.5 to 5. The possible acceleration at the site was set at 0.3 g. The possibility of an event at the site of a magnitude that could significantly affect the repository was determined to be very low.

No surface displacement or faulting younger than early Permian (Wolfcampian) has been reported, indicating that tectonic movement since then, if any, has not been noteworthy. No mapped Quaternary (last 1.9 million years) or Holocene (last 10,000 years) faults exist closer to the site than the western escarpment of the Guadalupe Mountains, about 100 kilometres (60 miles) west-southwest. The strongest earthquake on record within 290 kilometres (180 miles) of the site was the Valentine, Texas, earthquake of August 16, 1931, with an estimated Richter magnitude of 6.4. A Modified Mercalli Intensity V was estimated for this earthquake's ground shaking at WIPP. Since 1990, at least two seismic events have occurred that were recorded at WIPP. The Rattlesnake Canyon Earthquake occurred approximately 100 kilometres (60 miles) east-southeast of WIPP in January 1992. This event was assigned a Richter magnitude of 5.0 and occurred at a depth of approximately 12 kilometres (7.4 miles). This event had no effect on any of the excavations or structures at WIPP, as documented by post-event inspections by WIPP staff and the New Mexico Environment Department. An earthquake recorded at the WIPP site on April 14, 1995, was located 32 kilometres (20 miles) east-southeast of Alpine, Texas (approximately 240 kilometres [150 miles] south of the site). It was assigned a magnitude of 5.3 and is the largest event within 300 kilometres (185 miles) of the site since the Valentine, Texas, earthquake (Sanford et al. 1995). This event also had no effect on any excavations or structures at WIPP.

Based on a probabilistic seismic risk analysis and the region's historic seismicity, the strongest earthquake acceleration expected at WIPP would be 0.075 gravity (7.5 percent of acceleration because of gravity) with an average return period of 1,000 years. The design-basis earthquake (DBE) is conservatively assumed to be 0.1 gravity. Mine experience and studies on earthquake damage to underground facilities show that tunnels, mines, and wells are not damaged at sites having peak surface accelerations below 0.2 gravity.

### 3.7.7 Summary of approaches used and their application

Table 12 summarises the methods used in the WIPP evaluation programme and what they were used for.

<table>
<tr><th colspan="2">Information requirement</th><th>Method of measurement</th><th>Interpretation and modelling method</th></tr>
<tr><td colspan="2">Mapping (topographical, geomorphological and geological)</td><td>Existing geological survey data</td><td>This information is used as a basis for geological understanding.</td></tr>
<tr><td rowspan="4">Nature, distribution and properties of the sedimentary rock succession and salt dome</td><td rowspan="2">Lithostratigraphy and lithological variability</td><td>Geophysical logs from nearby hydrocarbon wells</td><td>Constraints on stratigraphy for stochastic flow models.</td></tr>
<tr><td>Boreholes; studies from collected cores, including four large diameter shafts at the WIPP site</td><td>Information on stratigraphy; which can be input into the geological model.</td></tr>
<tr><td>Lateral continuity and thickness of the formations</td><td>Investigation and monitoring of the subsurface geology using surface and borehole geophysical survey methods<br>Including geophysical logs for 90 boreholes through Culebra member</td><td>Used for site characterization investigations and monitoring – particularly to assess the thickness of salt, continuity of layering,</td></tr>
<tr><td>Geochemical properties of the host rock(s)</td><td>Characterization and modelling of hydrologic and geochemical characteristics of the Culebra Formation</td><td>Geochemical signatures help constrain the origin of groundwaters. Findings are input into 3D modelling of groundwater flow.</td></tr>
<tr><td colspan="2" rowspan="2">Geological structure</td><td>Hydraulic testing and tracer testing within the Culebra Dolomite</td><td>Used to assess homogeneity of the Culebra dolomite due to fracturing and varied geological composition.</td></tr>
<tr><td>Gravity data - microgravity</td><td>Microgravity surveys input into a model which can support borehole data to interpret the presence of potential faults or karst within the formations at the WIPP site, as well as variations in porosity and permeability.</td></tr>
<tr><td colspan="2">Tectonics</td><td>Seismic data - seismology</td><td>Determination of earthquake likelihood and intensity by measurement and monitoring of seismic activity.</td></tr>
<tr><td colspan="2">Spatial heterogeneity</td><td>Geophysics using TDEM methods (Time-Domain Electromagnetic); electrical profiles are generated and interpreted</td><td>Characterization of the pressurized brine occurrences. High conductivity in electrical profiles indicates the presence of brine reservoirs.<br>Results from the surveys were used to identify and characterise dissolution breccia pipes;these are fracture porosity brine reservoirs in the Castile formation.</td></tr>
<tr><td colspan="2">Spatial heterogeneity</td><td>Hydraulic testing and tracer testing within the Culebra Dolomite</td><td>Used to assess homogeneity of the Culebra dolomite due to fracturing and varied geological composition.</td></tr>
<tr><td colspan="2">Geotechnical/engineering properties of the host rock</td><td>Hydraulic testing and tracer testing within the Culebra Dolomite</td><td>Predictions of pressures required to fracture repository rocks can be calculated from these results.</td></tr>
</table>

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Hydrogeology** | **Hydrogeological monitoring** | Water level changes in observation wells north and south and in the vicinity of the WIPP | Monitoring which feeds into modelling of groundwater sources, giving insights into confinement and connectivity within the complex hydrogeological regime. |
| | **Hydrology of the geological formations** | Investigation and monitoring of the subsurface geology using surface and borehole geophysical survey methods. Including geophysical logs for 90 boreholes through Culebra member | Used to test and define conceptual models (e.g. the presence of high groundwater transmissivity zones in the Rustler Formation) and input for groundwater flow modelling. |
| | | Hydraulic testing of the Salado Formation | Characterization of brine flow within the Salado Formation; allows modelling of the interactions between gas generation, brine flow into the repository and contaminated brine flow out of the repository.<br>Determination of permeability – this was found to be very low.<br>Used to assess brine flow around excavations (DRZ). |
| | | Hydraulic testing and tracer testing within the Culebra Dolomite | Used to produce a multi-rate groundwater transport model. |
| | | Single and multi well aquifer tests | Fed into a hydrologic conceptual model, which was used to create model of groundwater flow pathways. This supports a determination of hydraulic diffusivity. |
| **Hydrogeology** | **Hydrology of the geological formations** | Hydraulic testing and hydrogeological measurements for 90 boreholes – including slug and constant-flowrate pumping tests | Calculation of hydraulic properties; hydraulic conductivities and molecular diffusion coefficients, determination of permeability.<br>Input into conceptual modelling of regional groundwater flow in units above and below the Salado Formation, particularly the Rustler Formation, which overlies the Salado and includes the more permeable Culebra Dolomite.<br>Findings are input into 3D modelling of groundwater flow. |
| | | Geophysical logs from nearby hydrocarbon wells | Constraints on stratigraphy for stochastic flow models. |
| | | Boreholes; studies from collected cores, including four large diameter shafts at the WIPP site | Hydrological properties of the formations present can be identified.<br>Input into hydrogeological characterisation; numerical flow and radionuclide transport models |
| | **Geochemistry of groundwater** | Geochemical analysis of brine from brine reservoirs | Determines primary brine origin in the Culebra formation. Groundwater is neither sourced from, nor mixed with, meteoric waters, and is saturated with salts from the surrounding Halite.<br>Helps to understand groundwater flow paths in the stratigraphy, migration from recharge areas etc. |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* |
|---|---|---|---|
| **Radionuclide diffusion potential** | **Groundwater flow pathways** | Single and multi well aquifer tests | Used to model groundwater flow pathways, essential for radionuclide transport model. |
| | **Radionuclide diffusion measurements** | Hydraulic testing and hydrogeological measurements for 90 boreholes – including slug and constant-flowrate pumping tests | Calculation of hydraulic properties; hydraulic conductivities and molecular diffusion coefficients, determination of permeability, as parameters for numerical flow and radionuclide transport models. |
| **Long term stability of the engineered barrier** | | Investigation and monitoring of the subsurface geology using surface and borehole geophysical survey methods<br>Including geophysical logs for 90 boreholes through Culebra member | To examine the effects of excavations; definition of the Disturbed Rock Zone (DRZ) that occurs around the underground excavations at the WIPP. |

**Table 12** Summary of data collected from hydrogeological, geophysical, and geological investigation techniques with an explanation of their use for characterisation of the WIPP site. Summarised from Borns (1997) and Kuhlman and Barnhart, (2011).

## 3.8 SUMMARY

This Chapter has provided a comprehensive account of the identified examples and illustrates the development of techniques, data handling and interpretation and geological model development in different national programmes (as specified in the first objective in Section 2.1). Most specific techniques to obtain geological data are common to all the examples e.g. surface geophysics, seismic surveys, use of geological and geotechnical information from boreholes. The level of sophistication in interpreting the information so that it can be used in geological site models appears to be a function of the complexity of the geological setting and when the programme was operational. For example, the Nirex Sellafield example is a good illustration of practice in the 1990s for preliminary site selection in a complex geological setting. The Swedish and Finnish programme examples are more recent, albeit with a relatively less complex geological setting, and show how the development of site description models can be used iteratively to move from a regional scale geological model to a site model. Additionally, the Swedish examples illustrate how additional methods and data sets, such as hydrogeochemical information and material testing methods, are used to develop regional and site models, but are reported elsewhere.

Table 13 summarises the approaches found most useful by the programmes discussed in this chapter.

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* | *Example programmes* |
|---|---|---|---|---|
| **Mapping (topographical, geomorphological and geological)** | | Field surveys, existing geological maps. Can include fracture mapping. | Used for geological models and to determine the main features of the geological environment. | Bure, Forsmark, Laxemar, WIPP, Nagra, Sellafield, Gorleben Olkiluoto |
| **Nature, distribution and properties of the sedimentary rock succession** | **Geometry, geological structure, and lithostratigraphy** | Geophysical logging in boreholes | Geometry and structure of geological formations. Identification of rock type and rock units. | Bure, Forsmark, Laxemar, WIPP, Nagra, Gorleben, Olkiluoto |
| | | Boremap mapping | Geometry and structure of geological formations. Identification of rock type and rock units. | Bure, Forsmark, Laxemar, |
| | | 2D seismic reflection survey. | Lateral continuity and thickness of geological formations. | Andra, Forsmark, Laxemar, Nagra, Sellafield,Gorleben, Olkiluoto |
| | | 3D seismic reflection survey | Geometry and lithological variability of the host rock and overlying formations. | Andra, Nagra, Sellafield, Olkiluoto |
| | | Lithology of the geology from sampled boreholes and shafts | Stratigraphy and lithology of the rock formations. | Andra, Forsmark, WIPP, Nagra, Sellafield, Gorleben, Olkiluoto |
| | | Airborne geophysics | Data can to help identify major fault structures | Forsmark, Laxemar, sellafield, Olkiluoto |
| | | Surface geophysical investigation | Used for site characterization investigations | WIPP |
| | **Mineralogical characterisation of the host rock(s)** | Determination of physical properties of the host rock e.g. permeability, mineralogy | Used for modelling and characterisation of the host rock. | Andra, Forsmark, Laxemar, Gorleben |
| | **Geochemical properties of the host rock(s)** | Characterization and modelling of hydrologic and geochemical characteristics of the host rock | Geochemical properties of rock types. Geochemical signatures help constrain the origin of groundwaters | Andra, Forsmark, Laxemar, WIPP |
| **Geological structure** | **Interpretation of structural domains from discontinuity data, fault and deformation zone locations** | 3D seismic reflection survey. | Survey results provide detailed information of the subsurface; can identify structural disturbances, fault locations | Andra, Nagra, Sellafield, Olkiluoto |
| | | 2D seismic reflection survey. | Survey results can identify structural disturbances, fault location. | Andra, Forsmark, Laxemar, Nagra, Sellafield, Gorleben, Olkiluoto |

| *Information requirement* | | *Method of measurement* | *Interpretation and modelling method* | *Example programmes* |
|---|---|---|---|---|
| **Geological structure** | **Interpretation of structural domains from discontinuity data, fault and deformation zone locations** | Seismic refraction data | Identification of deformation zones. Input for DZ modelling. | Forsmark, Lazemar, Nagra, Gorleben |
| | | Borehole logging - geophysical | Faults are detected. Used for calculation of confinement capacity. | Andra, Forsmark, Laxemar, Nagra, Gorleben, Olkiluoto |
| | | Boremap mapping | Assesses ductile deformation in the bedrock, fracture statistics. Data used to identify brittle deformation zones. Rock domain, DZ and DFN modelling. | Forsmark, Laxemar |
| | | Magnetic surveys | Identification of magnetic lineaments. Input for DZ modelling work | Forsmark, Laxemar, Nagra |
| | | Gravity data and interpretation | Verification of regional rock domain, geophysical modelling | Forsmark, Laxemar, WIPP, Nagra |
| | | Seismic velocity measurements along excavations across lineaments | Identification of deformation zones. | Forsmark |
| | | Characterisation of deformation zones, fracture mapping | Focussed lineament investigations, MDZ studies and outcrop structural investigations. Input for DZ modelling. | Laxemar, Sellafield |
| | | Hydraulic testing and tracer testing. | Used to assess fracturing and varied geological composition. | WIPP |
| **Tectonics** | | Seismic monitoring | To monitor earthquakes and tectonic activity | Andra, WIPP, Nagra, Gorleben, Olkiluoto |
| | | In situ stress measurements - convergence and extensometer measurements - overcoring method | Measurement of the natural stress field in the geological formation. | Andra, Nagra, Gorleben, Olkiluoto |
| **Spatial heterogeneity** | | Aeromagnetic survey | Additional data feeds into geological model of the area | Andra, Forsmark, Nagra |
| | | Gravity survey. | Additional data feeds into the geological model of the area | Andra, Sellafield |
| | | Electromagnetic surveys; electrical profiles are generated and interpreted | Used to assess the homogeneity of salt domes. | WIPP, Gorleben |
| | | Hydraulic testing and tracer testing, including hydraulic packer tests, and fluid logging in boreholes | Homogeneity of the formation due to fracturing and varied geological composition. | WIPP, Nagra |

**Table 13** Summary of key approaches used by the seven programmes reviewed in this report.

The programmes reviewed here have used a wide range of methods for the modelling and interpretation of geological data, many of them ‘borrowed’ from the hydrocarbon industry. Those found particularly useful are noted below.

The trial 3D seismic survey carried out during the Nirex Sellafield investigations was one of the first undertaken on-shore and it provided a large amount of data to refine the geological model of the PRZ area, in particular down to the top of basement (seismic imaging in the basement was not as good as in the cover rocks). As well as structural geological information the data were integrated with core and wireline derived information and processed to derive rock quality and hydrogeological indices.

The integration of core discontinuity data with information derived from borehole imaging and with dynamic features (e.g. the PFF logging at Sellafield) was a key process in understanding the site’s flow regime, not only the current regime but also palaeoflow regimes.

The development of BOREMAP and its application to the two sites investigated by SKB ensured a rigorous and consistent approach to borehole data handling that was invaluable in the development of the 3D geological models of the sites. Modelling and the general development of understanding of the sites was facilitated by the staged development of the site descriptive models (with associated data freezes) that was adopted by SKB.

Andra have found the geological interpretation that their 3D seismic survey of particular value in understanding their site. They expect that the spatial heterogeneity work that is being undertaken using the 3D seismic data will be very helpful in identifying the best horizon within the Callovo-Oxfordian clay within which to construct the repository galleries. Based on their GoCAD 3D geological model and their digital data repositories they are developing Geovisionary as a tool to both interrogate point data and for the visualisation of their site and proposed repository as part of their public engagement programme.

Nagra consider that the information gained from 3D seismic surveys allowing the development of the geological interpretation of a site area is an important tool in their geological investigation.

# 4 Other Sectors

This Chapter examines the application of various technologies and techniques in other sectors, including hydrocarbon exploration, for the interpretation and modelling of geological information. This is particularly applicable to sedimentary environments. The chapter addresses the second objective as outlined in Section 1.2 namely the inclusion of 'Any additional processes and tools that are used in other sectors for processing, interpreting and modelling data acquired through site characterisation that may be applicable to a UK-based waste management site characterisation programme'. It also addresses, but to a lesser extent, the third objective 'The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in the UK'; which is more explicitly addressed in Section 5.

For most of the interpretation and modelling applications discussed in this report the hydrocarbon sector has led the way in the interpretation and modelling of geological information. This means that methods and approaches are largely focussed on the needs of this sector and are particularly appropriate in sedimentary geological environments (and so are applicable to carbon capture and storage (CCS) also). This chapter will therefore discuss CCS as an example of how hydrocarbon industry techniques are being utilised in a developing technological sector which in many ways is similar to the studies undertaken for radioactive waste disposal. Because of the comprehensive use of modelling and interpretation technologies in the CCS sector this is described first. The other sectors described here are dealt with 'by exception' because most of the methods adopted are very similar to those used in the CCS sector. The groundwater and mining sectors are to a degree smaller players and the application of techniques for interpretation and modelling generally less sophisticated.

## 4.1 CCS AND GAS STORAGE

A very large international collaborative research programme funded by industry, government departments and the European Union for the last twenty years has established Best Practice for the storage of $CO_2$ in saline aquifers, which is based on hydrocarbon industry experience (Chadwick et al., 2008). Many of these practices lead to the development of geomodels; and the techniques are applicable (with modification) to related issues such as sub-surface gas storage.

### 4.1.1 Storage site characterisation

The principal aim is to confirm storage capacity and to provide the geological information necessary to show that the site will perform effectively and safely.

#### 4.1.1.1 Geological characterisation

The key datasets for a robust characterisation of the reservoir and overburden are a regular grid of 2D seismic reflection data sufficient to characterise reservoir structure and extents; a high quality 3D seismic volume over the injection site and adjacent area, tuned for satisfactory resolution of both reservoir and overburden; and sufficient well data to characterise reservoir and overburden properties. These datasets are most conveniently handled by means of hydrocarbon industry seismic interpretation software, such as Petrel, running on a digital workstation. Over the last 15 years, improvements in 3D acquisition and processing pioneered by the hydrocarbon industry, coupled with a dramatic increase in computer processing power, have led to significant advances in sub-surface characterisation. As a result, 3D seismic surveying would form the backbone of any future detailed sub-surface site investigation for CCS because, though expensive, such a survey allows the geology and structure to be well understood and for borehole sites to be optimised to provide the information required. 3D seismic surveys are now routine in the hydrocarbon industry in general.

#### 4.1.1.2 Reservoir structure

It is necessary to characterise the reservoir structure on both local and regional scales to elucidate $CO_2$ migration patterns and bulk storage potential. This requires structure mapping of depth to the top of the reservoir, reservoir thickness and compartmentalisation. The accuracy of the depth conversion depends on the number and distribution of well data, and, crucially, on the availability of well–calibrated sonic logs plus vertical seismic profiling (VSP) data and checkshots to ensure a good 'tie' to the seismic data. It is important to identify and map any faults, and to assess fault-sealing capacity.

#### 4.1.1.3 Reservoir properties

Lithological and petrophysical data are derived from wells in the vicinity of the storage location. It is essential to assess the lateral and vertical variation of sedimentary facies and fluid flow properties, because these control the evolution of the injected $CO_2$ plume. It is particularly important to recognise the presence of internal baffles, such as shale layers, and compartments, e.g. caused by faulting. Net-to-gross ratio, porosity and water saturation are determined using calibrated downhole geophysical log suites. Permeability is more reliably estimated from core samples. The latter are analysed by optical and electron microscopy, mineralogical analysis e.g. X-ray diffraction, and to determine mechanical, thermal, acoustic and elastic properties. Where possible, information from outcrop analogues is incorporated and geostatistical or stochastic methods of 3D reservoir model building may be useful.

#### 4.1.1.4 Caprock properties

Of particular concern is the capillary sealing efficacy of the caprock and its geomechanical stability. For long-term integrity, capillary entry pressures should be well in excess of any likely pressure increase due to the injection process or to the buoyancy-driven accumulation of $CO_2$. These parameters are determined by rigorous laboratory tests, including those already outlined in section 4.1.1.3 above. Upscaling of such test results to entire boreholes and rock volumes is achieved using modelling software within Petrel.

#### 4.1.1.5 Overburden properties

Knowledge of the overburden overlying the caprock is also important in the context of multibarrier/multireservoir storage systems, and for the monitoring of leakage. The techniques of analysis and modelling are comparable to those described in section 4.1.1.4 above.

#### 4.1.1.6 Fault properties

It is known that faults can be transmissive or sealing to $CO_2$. Using conventional seismic sources in areas of simple structure, faults with throws of the order of 10 m can be detected at shallow depths. At greater depths, throws of 20 m may be detectable. In areas of more complex structure, more sophisticated processing steps such as depth migration and pre-stack depth migration are required to obtain subtle and spatially accurate detail. For optimal reservoir engineering, faults should be sealing in the caprock to prevent leakage but also transmissive in the reservoir to avoid excessive pressure build-up. Increased fluid pressure during $CO_2$ injection may reactivate faults to induce leaks. Reservoir performance in general, and fault behaviour in particular, remain poorly constrained and it is not yet possible to predict storage performance in saline aquifers to the onerous standards implied by the EU CCS Directive.

### 4.1.2 Predictive flow modelling

All the information gathered in the site characterisation is built into a 3D depth geological model, which is attributed with reservoir and overburden parameters, including up-scaled information from well geophysical and laboratory testing. The model is then loaded into flow modelling software such as ECLIPSE. A useful early modelling tool is a simple buoyant 'ponding' simulator, such as SEMI, which can assess the early behaviour of the buoyant $CO_2$ plume.

### 4.1.3 Site monitoring

During the lifetime of a $CO_2$ storage site, the amount and movement of gas in the reservoir and its surroundings will be carefully monitored using a number of tools, as identified by Chadwick et al. (2008). The tools include geophysical methods, particularly 3D, time-lapse 4D, multicomponent seismic (see section 4.1.4 below), microseismicity and microgravimetry, geochemical methods and remote sensing. All of these methods can be used and modelled in time-lapse mode, so that changes in the site can be readily identified. From this the predictive models of site performance can be calibrated, tested or adjusted, as necessary. A secondary objective of deep monitoring systems is to give early warning of migration to shallower depths. 4D time-lapse seismic is likely to prove the key subsurface monitoring tool in many storage scenarios, and excellent results have already been obtained at moderately deep storage sites in the Norwegian offshore (Chadwick et al., 2008) and the Canadian onshore (Wilson and Monea, 2004). However, reservoirs will generally show significantly impaired seismic response with increasing depth of burial (McKenna et al., 2003).

### 4.1.4 Assessment of the rock mass

The wide availability of high-resolution 3D seismic data has led to the development of new techniques to obtain enhanced rock property information from the seismic volume, and thus of the rock mass, under investigation. These techniques exploit the fact that seismic measurements such as velocity, frequency and amplitude vary with offset and azimuth. In addition to compressional (P-) wave data, multi-component seismic data can be used to provide estimates of Poisson's ratio (an important geotechnical rock property), information on fracture density and orientation, pore fluids and lithological data. Although shear (S-) wave sources are available, the mode-converted PS wave generated under the appropriate acquisition parameters frequently gives superior quality images. The cost of acquiring multicomponent seismic datasets is more expensive than for 3D P-wave datasets; in the order of 1.3 to 2.3 times higher onshore; and between 5 and 10 times as expensive offshore.

#### 4.1.4.1 Enhanced seismic imaging

Multi-component seismic was initially developed by the hydrocarbon industry to image beneath gas accumulations which preferentially absorb P-wave energy and degrade image quality. Shear waves are not thus affected. When applied to shallow sedimentary sequences, a marked improvement in seismic imaging may result (e.g. Stewart et al., 2003).

#### 4.1.4.2 Sub-seismic scale fracture characterisation

Unlike P-waves, S-wave anisotropy occurs and can be detected along all propagation directions, making multi-component seismic imaging a robust tool for the determination of fracture density and orientation (e.g. Liu et al., 2003). When a polarised S-wave enters an anisotropic medium it splits into two waves, one, with higher velocity, travelling parallel to fractures in the medium, the second (with lower velocity) propagating 90deg apart. The polarisation of the first shear wave records fracture direction; the time delay between the waves reveals the fracture density. Measurement of fracture-induced seismic anisotropy has proved to be a key factor in the exploitation of fractured oil and gas reservoirs. The method provides very useful information on the likely plume propagation direction of gas injected into saline aquifers. It may also find application in the shale-gas industry, where the density and orientation of fractures is a key constraint on the 'frackability' of the gas-bearing shale horizons.

#### 4.1.4.3 Geomechanical characterisation

Small changes in pore pressure can cause large changes in S-wave velocity, which can be resolved by multi-component seismic data. This technique has been applied to studies of unconsolidated and overpressured sands which have the potential to compromise the integrity of oil wells; but potentially has application in other fields of geomechanical investigation, e.g. the estimation of pore fluid pressure in solid rocks (Li et al., 2007).

#### 4.1.4.4 Multi- (and wide-) azimuth seismic acquisition

High velocity layers such as salt and basalt have very high elastic impedence contrasts with the regional sedimentary framework, degrading the quality of the conventional P-wave image beneath. These regions may be more successfully imaged using multi-component acquisition procedures e.g. wide- and multi-azimuth geometries now commonly used in marine seismic surveying. Other possible applications are in areas of complex and heterogeneous structure, such as orogenic thrust belts.

#### 4.1.4.5 Lithological discrimination seismic inversion

Seismic inversion exploits the fact that seismic velocity, reflection amplitude, phase and frequency are all controlled by the material properties of the rock matrix and pore fluid. In addition amplitude and velocity variation with source-receiver azimuth can provide information on fracture orientation and density. Seismic inversion schemes are conducted using pre-stack data in which seismic amplitudes are carefully preserved. The amplitude variation with offset (AVO) technique can be used to generate attributes such as the Scaled Poisson's ratio, an elastic impedence approximation and the Lamé constants for rigidity and incompressibility (Ross, 2002), all useful geomechanical parameters for site characterisation. Amplitude variation with offset and azimuth (AVOA) can be used to extract information about fabric anisotropy from wide azimuth seismic data e.g. sedimentary layering or vertical, parallel cracks. Joint inversion of PP and PS multi-component seismic data allows VP/VS ratio and Poisson's ratio to be calculated. The latter are frequently a good indicator of rock type (Stewart et al., 2003).

## 4.2 HYDROCARBON EXPLORATION/EXPLOITATION INCLUDING SHALE GAS

The site characterisation modelling and interpretation activities described above for CCS is equally applicable to the exploration for and exploitation of conventional hydrocarbon resources. These are not repeated here. The principal difference is that for hydrocarbon exploration 4D (time lapse) seismic surveys (see Section 4.1.3 above) are not undertaken and they are only rarely undertaken during the exploitation of reservoirs.

The hydrocarbon industry is increasingly exploring for and evaluating resources in 'hard' rocks, be they fractured sedimentary strata as in the Claire field west of Shetland or even in some cases fractured basement or granitic rocks such as in Vietnam. Such rocks, and the seismic imaging of the rocks beneath salt deposits, are difficult to image using traditional seismic methods and the recent development of the Controlled Beam Migration (CBM) method of seismic data interpretation has enhanced the ability to image these rock types (Vinje et al 2008). In effect CBM is an enhancement to more conventional pre-stack depth migration of seismic data for imaging complex geological environments. The main benefits of CBM are the enhancement of the signal-to-noise ratio of images and the enhancement of steep dips both of which are valuable for imaging complex geological structures and fractures in otherwise relatively uniform 'basement'.

Microseismicity monitoring and modelling (see Section 4.1.3 above) will be an important part of development of shale gas production, where hydraulic-fracturing (colloquially known as 'fracking') of the host rock is an important process in exploiting shale gas resource.

## 4.3 MINING INDUSTRY

The mining industry can be split into 3 different sectors:

- Coal mining (and related coal bed methane (CBM) and in-situ gasification (ISG));
- Bedded ore and related deposits;
- Non-bedded ore and related deposits.

Each of these sectors is dealt with separately below.

### 4.3.1 Coal Mining

Exploration for both traditionally mined (open pit and deep mined) coal reserves and for the exploitation of CBM and of coal by ISG is undertaken primarily using, mainly 2D, seismic survey data combined with information from geological mapping and boreholes. Infrequently airborne geophysical survey data has been used to guide the geological interpretation. 3D digital geological modelling is often undertaken for development of coal resources, for example the UKs National Coal Board used Vulcan extensively for modelling both open pit and deep mine coal projects.

### 4.3.2 Bedded ore and related deposits

Exploration for bedded ore and related deposits, such as iron ore, salt and gypsum, is generally less sophisticated than that for coal with the development of an understanding of the geology, perhaps supported by information from boreholes and, depending on resource targeted, information derived from interpretation 2D seismic surveys, airborne and surface based non-seismic geophysical surveys.

### 4.3.3 Non-bedded ore and related deposits

The exploration for mineral veins and a wide range of other non-bedded deposits is similar to that undertaken for bedded ore deposits though seismic survey data is rarely used in the evaluation of such resources. A mineral exploration programme will usually evolve with the development of an understanding of the geology and the potential to host the resources sought. This will be followed up by regional scale geochemical surveys, airborne and surface based non-seismic geophysical surveys, the methods used depending on the targeted resources and setting. Borehole drilling and wireline logging (probably relatively simple logs when compared to the hydrocarbon and coal industries noted above) to obtain detailed information will only be undertaken to gain an understanding of any 'anomalies' identified by the surveys. While the geological interpretation of a target will probably include the development of a number of geological cross-sections it is unlikely that 3D geological modelling will be undertaken unless potentially economic resources are identified.

## 4.4 APPLICATIONS OF THREE-DIMENSIONAL GEOLOGICAL MODELLING IN GEOLOGICAL SURVEY ORGANISATIONS

Applications that benefit from 3D modelling in Geological Survey Organisations (GSO) have been defined by Berg, et al (2011) as:

- Water - regional scale studies describing the major aquifers and non-aquifers that support groundwater management. Local-scale studies may include groundwater flooding and contaminant transport;

- Waste disposal, management and contamination - characterisation of groundwater systems for assesment of risk assiciated with waste disposal associated with the nuclear industry, hazardous waste, refuse sites, mass-burial sites, underground storage tanks, and many other contaminants;

- Hydrocarbon, energy, and Carbon Capture and Storage - modelling of oil and gas reservoirs, modelling thickness and quality of coal reserves, capacity and suitability assessment of reservoir rocks for $CO_2$ sequestraion;

- Land-Use Planning - aiding decision making in land-use planning by modelling water and mineral resources to better inform planners;

- Civil engineering and infrastructure - site investigation modelling for construction projects, and linear route assessments for utility and transport infrastructure;

- Mineral resources - resource and reserve assessment at regional and local scale, often accompanied by environmental impact reporting. Mineral resource modelling can also help with balancing the need for resource extraction with competing land uses;

- Research - 3D modelling has opened new approaches and discoveries in earth science, allowing visualisation and interpretation of 3D geological structures over entire countries or small, high-resolution areas in new ways;

- Education and outreach - visualisation and communication of 3D structures to students and public, greatly increasing understanding.

### 4.4.1 Datasets required for 3D Geological Modelling

Berg, et al (2011) have identified the datasets required for construction of 3D geological models by GSO.

There is a suite of data sets that ranges between obligatory and helpful for the development of a sound 3-D geologic map or model. The determination of whether a specific data set is obligatory or optional can be somewhat subjective and is dictated by the specific software and workflow or the perspectives of the geologists involved with the mapping.

#### 4.4.1.1 Digital Terrain Models

A digital terrain model (DTM) of the proper resolution and extent for the map area, also known as a digital elevation model (DEM), is probably the most necessary data set for any 3-D mapping project. Because some 2-D mapping workflows still rely on hand drawing contacts on topographic maps, a given GSO may not be familiar with the requirements of acquisition and management of DTMs that meet the needs of specific 3-D mapping projects. Depending on the country, province, or state, acquisition of the necessary DTMs can range from easy to impossible and from free to prohibitively expensive.

#### 4.4.1.2 Borehole Drilling Logs

After acquisition of a suitable DTM, the availability of digital borehole driller's descriptions is probably the next most important data set. Data quality issues associated with borehole logs must be evaluated, because these data, depending on their location or quality, might not meet the needs of the project or mappers. The quality of these data must be evaluated early, as unidentified errors can result in boreholes being mislocated by significant distances. The referenced land-surface elevation of the borehole data must also be given consideration. Common practices suggest that the borehole elevations should be taken from the most detailed elevation source, regardless of the resolution of DTM used. Additionally, the quality of the geological descriptions can vary dramatically between individual records, which can significantly affect the value of these data for any mapping project. Finally, when potentially thousands of raw borehole data points are being visualized in 3-D for a site with a high density of data, many points can be in the same general location. This creates a problem when creating associated databases, and, to ensure data quality, the "best" data point may be selected to represent the site.

#### 4.4.1.3 Lithologic Dictionaries and Stratigraphic Lexicons

Lithologic dictionaries and stratigraphic lexicons are two additional geological data sets that should be considered when beginning the move to 3-D geological modeling. Although a dictionary that assigns standard lithologies to borehole driller's descriptions may not be required for a given software package or workflow, every project needs to define the formal mapping units that are included in the map area. The format of these data sets is wholly dependent on the software used for modeling.

#### 4.4.1.4 Colour Ramps

One of the last required data sets for any mapping project is the definition of a consistent color scale for all modeled units and properties. Development of internal standards can be worthwhile, but must be recognized as another option that each GSO must consider based on its resource base, timeline, and mapping project priorities.

#### 4.4.1.5 Optional Data Sets

Several optional data sets are commonly used in 2-D and 3-D mapping that are worth considering:

- Collection and compilation of digital versions of additional borehole data, outcrop descriptions, additional field observations, geophysical borehole logs, and geophysical profile data can all be helpful in providing additional insights on the distribution and character of the mapped deposits;

- Geological maps often are available for an area before 3-D modeling efforts begin. These maps can be very helpful in expediting a subsurface mapping effort, regardless of the software used. It is common, however, for the maps to be generated during the 3-D mapping effort, so these maps may not be available at the onset of a project;

- Access to digital topographic maps can be of significant value, depending on the products to be generated from the 3-D mapping effort. These topographic map layers should be appropriate in scale to the resolution of mapping and to the desired scale of final map products;

- Finally, available cross sections and other profile data can be scanned and georeferenced for position and used in many mapping software applications. The value of including these types of images needs to be weighed against the mapping objectives, timeline, and expense (time and staffing) of digitizing and georeferencing these data.

### 4.4.2 Common 3D Mapping and Modelling Software

Berg et al, (2011) describe several common software packages used for 3D geological mapping and modelling in GSO around the world:

- 3D Geomodeller - Originally developed by the French Geological Survey (BRGM) and commercialised by Intrepid GeoPhysics, this software uses borehole measurements, structural measurements and fault locations to create a model. Uniquely, Geomodeller also allows for full geophysical inversion modelling which is used for validation of the geometry-based results;
- ArcGIS - 3D Analyst extension, in particular ArcScene is used to visualise and model a variety of geological data. This generally requires customisation of the software with VBA and ArcObject scripting;
- earthVision - Dynamic Graphics offering is a very powerful tool used extensively in the oil and gas industry, but is also suitable for modelling in near-surface 3D mapping and modelling projects;
- GOCAD - Originally developed at Nancy University in 1989 by Professor Jean-Laurent Mallet. Now developed and marketed by Paradigm. GOCAD has an active academic research group and is probably the most widely used subsurface modelling package in GSOs. It has an intuitive structural modelling workflow that is simple and intuitive. GOCAD is also widely used in the Oil and Gas industry for reservoir modelling;
- GSI3D - Developed by Hans-Georg Sobisch in collaboration with the Geological Survey of Lower Saxony and latterly the BGS, GSI3D attempts to replace the common working practices of geologists with a software methodology that uses Digital Terrain Models, surface geological linework and borehole data to create a fence-diagram of cross-sections that are then calculated into a block model. This was originally applied only to Quaternary and simple stratified geology but developments are underway at BGS to extend the functionality of the software into faulted bedrock environments;
- GeoVisionary - Virtalis, in partnership with the BGS, has created a high-resolution 3-D stereo-visualization package for visualization and interpretation of very large data structures that can accommodate elevation, imagery, and 3D models covering entire countries. GeoVisionary interfaces directly with ArcGIS to facilitate interactive map creation and editing;
- Isatis - Developed by Geovariance, Isatis is commonly used in GSOs for geostatistical modelling of porosity, permeability and uncertainty in models;

- Petrel - Schlumberger have developed this software for the petroleum industry and is particularly suited to modelling with 3D seismic data;
- Rockworks - By Rockware, is used in GSOs, but mainly in the petroleum, environmental, geotechnical and mining industries for visualization of subsurface data such as maps, logs, cross sections, fence diagrams, solid models and volumetrics;
- SKUA - Paradigm's flagship reservoir modelling, simulation and visualisation package, used primarily in the oil and gas industry, it has found use in some GSO to model properties in structurally complex geological settings;
- Move - Produced by Midland Valley Exploration, Move is a comprehensive toolkit for structural modelling and analysis;
- Surfer - By Golden Software. This is primarily a 2D gridding package, but can be used to create and visualise 'stacks' of modelled surfaces in 3D;
- Surpac - A specialist mining software toolkit by GemCom;
- Vulcan - By Maptec, this is another specialist mining software suite, encompassing the full mining process from primary data management to construction of bespoke databases and 3D models for mine planning and management.

### 4.4.3 Some of the lead players in GSO 3D Modelling

**Geoscience Australia** uses a range of different 2-D and 3-D modelling applications including Gocad, ArcGIS, ER Mapper, and PetroMod, depending on the professional subject area, the type of data being processed, and the desired output.

**Geoscience Victoria** primarily uses GOCAD, where the model constrains serial and seismic sections, and any other appropriate data sets and surfaces are visualized and analyzed.

**British Geological Survey:** of 500 BGS scientific staff, about 30% have been trained to use 3D geological modelling techniques and to employ these tools in primary surveys; coastal, urban, and engineering site remediation; and groundwater studies. Approximately 20 scientists are engaged in 3-D modelling on a daily basis. The modelling community is supported by a help desk and training courses. Software used is mainly GSI3D and GOCAD.

**Geological Survey of Canada**: The most common software used for modelling is GOCAD, with some use of MapInfo and Vertical Mapper, and also the ESRI suite of software.

**Bureau de Recherché Géologiques et Minières :** The French Geological Survey have about 10 geologists in the Geology Department regularly work on 3-D modelling. Ten additional staff are involved with modelling activities from other departments (e.g., Water, Geothermal, and Mineral Resources).

In serving its customers and meeting international standards, the BRGM uses these commercial software packages:

- Petrel (Schlumberger) and EarthVision (Dynamic Graphics) for simple geology and basin analysis;
- Isatis (Geovariance) for studies that need geostatistical analysis and quantification of uncertainty to assess resources;
- Surpac (GemCom) for mining projects that require construction of 3-D geological models for assessment of resources;

- 3D GeoModeller (BRGM-Intrepid Geophysics) for helping to define complex 3-D geology based on implicit modelling of surfaces; and
- MultiLayer/GDM (BRGM), which is specially suited for data control and for layered models where traditional geostatistics is particularly efficient.

**Illinois State Geological Survey:** Here, customised ArcScene is used, alongside Isatis. 3D Visualisation is handles by GeoVisionary and GSI3D.

**Manitoba Geological Survey** use GOCAD to model the Western Canada Sedimentary Basin, spanning Manitoba, Saskatchewan and Alberta.

**TNO – Geological Survey of the Netherlands** uses a toolbox consisting of several components:

- The geostatistical software package Isatis by Geovariance is the main modelling platform by which statistical data analysis is performed, semi-variograms are constructed, and interpolation procedures are conducted;
- ESRI's ArcGIS is used to create additional input data for the modelling, including fault patterns, maps showing the extent of lithostratigraphic units, and geological features such as channel belts;
- All surfaces that result from the 2-D interpolations in DGM, REGIS II, and GeoTOP are stored and presented in ESRI's raster format;
- Gocad is used for visualization of 3-D models and inspection of 2-D surfaces in 3-D displays;
- There is extensive use of the Python programming/scripting language to create specific programs that perform many tasks, for example: (a) converting data from one data format to another; (b) extracting borehole information from the DINO database and preparing it for input to Isatis; and (c) automating lithostratigraphic interpretation of boreholes.

**United States Geological Survey:** The primary software packages used for, or in support of, 3-D geological mapping in the USGS are EarthVision, 3-D GeoModeller, Move, RockWorks, ArcMap, Oasis montaj, SGeMS, Encom PA, and in-house software for geophysical modelling.

### 4.4.4 Geological Data Integration and Interoperability

Early work by the BGS under its Digital Geoscience Spatial Model (DGSM) project between 1999 and 2004 (Smith, 2005) and now much more widespread developed methodologies and systems (e.g. SIGMA) that allow smooth data flow between applications and from digital field capture through to data archive, GIS and eventual 3D model production. This is an integrated approach to field data capture through to map production and modelling activities. It includes pre-field visit assessment of all existing information to develop a preliminary geological understanding of the area under consideration which is in part used to identify areas for detailed field follow up.

Using GeoVisionary to organise and interpret existing data (which can be images, GIS, 3D models, geophysical data etc.) prior to commencing field work, combined with the BGS SIGMAmobile system, pre-loaded with the information previously prepared in GeoVisionary, for field data acquisition and submission of new data and interpretations to corporate data bases has greatly simplified field mapping and data collection. The various 3D geological modelling packages (mainly GSI3D and GOCAD in the case of the BGS) which can now be linked with GIS data for model construction and map style presentation, and the interoperability between these systems and the raw data means that production of geological models using a wide variety of data sources is now much simpler.

Finally the use of GeoVisionary, a unique geoscience visualisation tool developed by the BGS and Virtalis, which allows information from a wide variety of sources to be visualised, is a powerful means of sharing geological and other 3D information with a variety of technical and lay audience in a way that allows them, with guidance, to interact with the data. In collaboration with ANDRA, BGS has developed robust tools for interrogating and exploring spatial, time series data. Completed early in 2012, this allows the user to use GeoVisionary to access data held in external databases and, with the correct authorisations, to view, manipulate, visualise, update, add to and otherwise explore the data (in the case of ANDRA held in three different databases, but when operating within BGS potentially providing access to over 100 digital (mainly Oracle) datasets).

The above description is a very brief summary of how the BGS currently integrates existing data with new data acquisition to provide new 2D and 3D geological interpretations, maps and models. There are still developments ongoing to the systems and approaches, however, the systems are now relatively mature and used throughout the BGS.

#### 4.4.5 High resolution airborne surveys

The non-seismic geophysics field is one of rapid development and with advances in system design and computing power are allowing more advance data processing thus enhancing overall survey output quality. Perhaps the most useful is the development in high resolution geophysical surveying which as far as the authors are aware has not been utilised in any of the programmes reviewed in Chapter 3. Such surveys have been undertaken over several areas of the UK over the last 10 or so years and have also been undertaken by a number of other geological surveys including the Finnish and Irish surveys. In the UK since the trial area flown in 1998 over the north Midlands, the whole of Northern Ireland, the Isle of Wight and Anglesey (Figure 6) and several other areas in Great Britain have been surveyed. Flight line spacing of 200 m, with frequent tie lines, and ground clearance of 90 m in rural areas, increasing to about 240 m in urban zones are typical. The result is high quality, high resolution data particularly useful for geological interpretation (see Hunter and Shaw (2011) for an example the use of HiRES magnetic data from North Derbyshire for the interpretation of buried volcanic rocks). In addition to allowing detail interpretation of the geology, which is one of the prime drivers for the surveys undertaken, two important uses of such surveys are regional exploration for mineral resources (non hydrocarbon/coal) and assessment of shallow contaminant plumes.

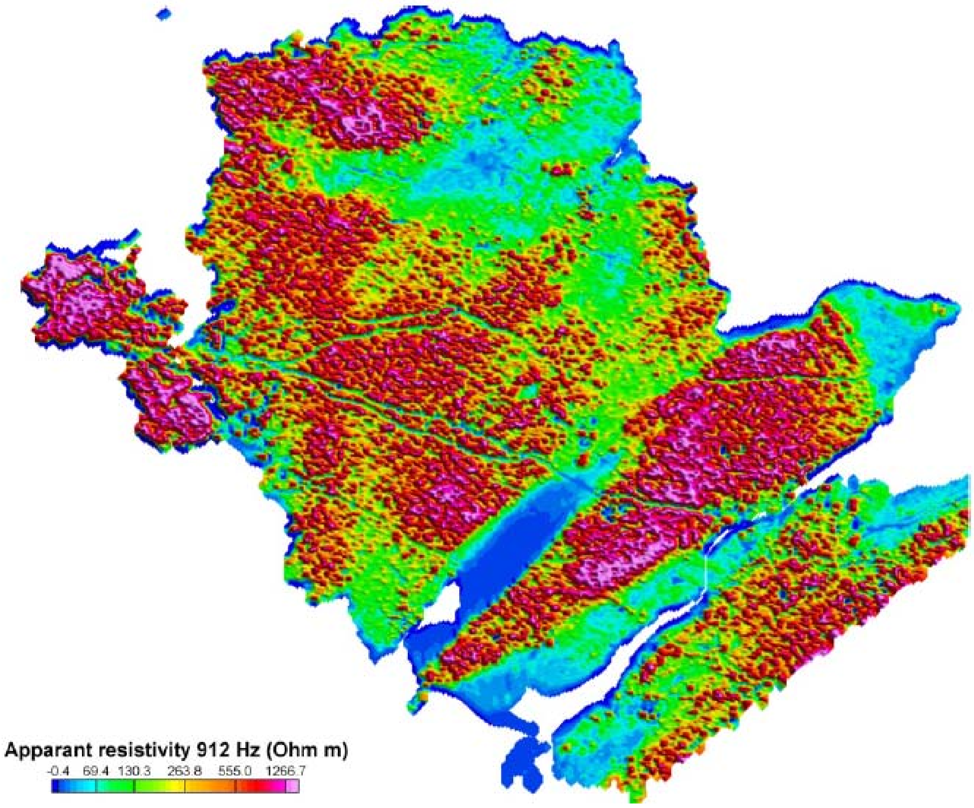



**Figure 6** Example HiRES data from the Anglesey survey, EM: Apparent resistivity, 0.912 kHz (from White and Beamish 2010).

### 4.4.6 Integrated Interpretation and Digital Field Mapping

The British Geological Survey (BGS) first explored the concept of integration interpretation and digital field data collection in the early 1990's, with the conclusion that the mobile computing hardware at that time was not suitable. The development was therefore postponed indefinitely. However, about ten years ago the BGS initiated a major new project, called SIGMA (System for Integrated Geoscience Mapping) to update its mapping systems and workflow. SIGMA is an integrated workflow for geoscientific surveying and visualisation using digital methods for geological data visualisation, recording and interpretation in both 3D and 4D. Today all BGS field work is undertaken using digital field data collection.

In 2000, the BGS began a new programme to move from production of maps to models. The Digital Geoscience Spatial Modelling programme recognised the fact that geology is a 3 and 4 dimensional subject and is best represented in a '3D map' – the traditional 2D map only shows the distribution of rocks at surface, or below superficial cover, whereas the 3D model shows the geometry of the geological units in a way that is easily understood by a non-geologist.

Digital field data capture is the primary method used by many national geological surveys to begin creation of 3D subsurface models. The survey data capture leads in directly to the 3D model, with geological boundaries and rock-types being mapped as 3D lines and other observations that feed directly into the modelling process. Without primary survey and other forms of data aquisition, including borehole and seismic data interpretation, there can be no reliable 3D models.

The approach adopted is one of pre-field visit loading of existing information into a digital environment to allow the field geologist to assess and interpret all available existing data prior to field work commencing. This allows the development of conceptual models, perhaps only mental ones or simple cross sections, of the area under consideration so that new field work can be targeted at addressing specific uncertainties. Once in the field, it is an integrated system that enables the full array of geoscientific data to be recorded using tick boxes, sketches, drop-down lists, tagged free text, and photographs where appropriate. Spatial location and navigation is gained by built-in GPS whilst the stylus enables points, lines, polygons, and comments to be added to the digital map face. Additional relational information is added using customized forms and a selection of interfaces. The system is modular, with tabs for various themes or domains of geological data such as structural readings, landslides information and auger/section recording etc. Furthermore, there are additional tools including the ability, to draw sketches, annotate photographs, produce structure contours, and navigate using bearings. All of the data collected are tagged with a unique user identifier (UUID) enabling them to be queried in the office and traced through the corporate repositories. At all stages during the field work phase the geologist is able to develop their understanding of the geology under consideration and progress their interpretation and development of conceptual geological models so that once field work is complete 3D geological modelling can be undertaken without the need for further interpretation.

The BGS no longer produces maps as an initial product of field mapping but uses the data acquired in the field to create a digital 3D geological model (normally using GSI3D software). This model incorporates the field data collected integrated with the any relevant geophysical data and represents the geologist's understanding of the 3D geology of the area under consideration. Once modelling for an area has been completed the digital model are used to generate the geological maps at 1:10,000 scale (which are simplified to 1:50,000 scale as required). The use of this approach facilitates data entry, handling and transfer to the 3D modelling software so that the subsequent modelling, which is undertaken by the mapping geologist who has already developed mental conceptual models of the area under consideration as part of the geological mapping process. GSI3D uses cross sections, constructed from real and virtual boreholes, as the basis of building the geological model.

Other geological surveys have also developed digital field data capture, for example the US and Canadian surveys and BGS co-operates with these, and other, surveys in these developments.

### 4.5 SUMMARY

Analysis of additional processes and tools that are used for site characterisation in other industries (as specified in the second objective in Section 1.2) shows that for many sectors, including carbon capture and storage and hydrocarbon exploration work, the interpretation and modelling of geological information is critical and is primarily focussed on the specific needs of that particular sector. Nevertheless, standard industry products are available for the baseline geophysical analysis and interpretation. Other more specific software packages are needed for more sophisticated modelling of such data. Much of this expertise is currently available in the UK and could be available for use for a site characterisation programme (as specified in the third objective in Section 1.2).

Approaches that are likely to be particularly useful from the sectors briefly reviewed above in a new UK site characterisation programme include:

- 3D seismic survey and derived information on spatial heterogeneity;
- Controlled Beam Migration (enhanced imaging in basement rocks);
- High resolution airborne geophysical surveys which would permit better geological interpretation at depth (in particular prior to drilling);

- Integrated mapping allowing assessment and interpretation of all available existing data prior to field work commencing and continuously as new information is acquired.

There is a wide range of commercially available software available to assist the modelling and interpretation of geological data. Of particular relevance to a new UK site characterisation programme are:

- GIS – widely used packages include:
    - ArcGIS
    - MAPINFO
- 3D modelling –packages widely used in a number of sectors include (rock type(s) under consideration may influence choice):
    - earthVision
    - GoCAD
    - GSI3D
- Integrated modelling and workflow tools (widely used in the hydrocarbon sector) include:
    - Petrel
    - Skua

# 5 Resources

This chapter addresses the third objective as outlined in Section 1.2 discussing 'The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in the UK'. It also partially addresses the final objective 'The identification of any gaps in available resources to support a UK-based site characterisation programme'. It provides a summary of the tools for geological interpretation and modelling that could be used in undertaking a site characterisation programme. It also provides information on the potential availability of expertise to use such tools. While the use to which the geological understanding of a site developed during a site characterisation programme is very specific and perhaps also involves the characterisation of geological environments less commonly examined by other sectors, the fundamental approach is very similar to, for example, hydrocarbon exploration.

There are three principal categories of activities required to support the interpretation and modelling activities needed to develop the geology discipline-based model. These are:

- 3D modelling;
- GIS; and
- Geophysical data processing.

Each of these activities has three components comprising software, hardware and the expertise needed to use them. Software for all three of these activities are readily available commercially, either to purchase or as a service, and it is highly unlikely that software development will be required for a UK site characterisation programme. The hardware requirements for the majority of the applications are no more than high performance PC computers though in a few cases software is optimised to run on a workstation rather than a PC. Similarly experienced operators are also available use these systems.

## 5.1 3D MODELLING HARDWARE AND SOFTWARE

A number of digital 3D geological modelling software packages are available that run on desk top PCs or similar. Current software has mainly been developed for use by the hydrocarbon or mining industries and is widely used in the related CCS and shale gas sectors. As such in many cases the software was specifically designed for use in sedimentary geological environments rather than for hard rock environments. While this does not mean that they cannot be used for modelling a hard rock environment their use in such geologies may be slightly less straightforward.

Software widely used included:

- earthVision (Dynamic Graphics Inc.) – specifically developed for use by the hydrocarbon industry and particularly suited to modelling sedimentary geological environments;
- GoCAD (Paradigm) – developed by Nancy University who continue its development through a largely academic consortium but the software is commercially marketed through Paradigm. GoCAD was originally developed in particular to model complex

folded sedimentary strata but is now widely used for many geological environments;

- GSI3D (BGS) – developed for modelling Quaternary (superficial) strata but now particularly suited to modelling all sedimentary geological environments;

- Landmark (Haliburton) – specifically developed for use by the hydrocarbon industry and particularly suited to modelling sedimentary geological environments;

- Petrel (Schlumberger) – again widely used in the hydrocarbon industry and particularly suited to modelling sedimentary geological environments;

- Vulcan (Maptek) – Specifically developed for mine design and ore reserve modelling in all geological environments.

Because of the different primary purposes that these packages were designed for they do not all model all geological environments easily and require different levels of expertise to operate though all have become more user friendly and intuitive with continued development.

Other modelling packages include:

- DecisionSpace Earth Modelling (Landmark Graphics Corporation);

- Geomodeller3D, (Intrepid Geophysics);

- Geocap;

- IRAP RMS Suite (Roxar);

- Leapfrog (Aranz Geo Ltd);

- Minex, Surpac and GEMS (Gemcom Software International);

- SKUA (Paradigm).

## 5.2 GIS SOFTWARE

A wide range of both proprietary and open source GIS (Geographical Information System) software packages are readily available to run on PC. Two of the most commonly used proprietary GIS applications, though there are a number of other applications, are:

- ESRI's ArcGIS
- MapInfo Professional

Traditionally 2D products have gradually increased their ability to manage, visualise, analyse and edit 3D data, through extensions to the core product. ArcGIS has a 3D Analyst extension as well as two applications for visualising 3D data: ArcGlobe (for viewing GIS data on a 3D Globe) and ArcScene (generating perspective scenes that allow navigation and interaction with 3D feature and raster data). MapInfo Professional now includes a 3D viewing capability as well as the ability to integrate full 3D functionality through packages such as Encom Discover 3D (intended for 3D geosciences applications).

3D models can be used and imported from 3D modelling packages in one of two ways:

- True 3D data. The 3D information is stored for each object in the feature's geometry. 3D data can support volumes and potentially many different Z-values for each X,Y location. For example, a vertical line has an upper vertex and a lower vertex, each with the same 2D coordinate, but each having different Z-values.
- Surface data (commonly called 2.5D). Surface data represents height values over an area, and the 3D information for each location within that area can be either stored as cell values or deduced from a triangulated network of 3D faces. Surface data cannot generate volumes and supports only a single Z-value for each X,Y location. For example, the height above sea level for the surface of the earth will only return a single value.

Whilst true 3D modelling is not yet part of mainstream GIS, and is often subject to poor performance, especially when visualizing complex 3D data, it is clear that with the increased requirements for modelling 3D data, and fast improving technologies that support this requirement, the 3D data capabilities of GIS packages will improve rapidly and become more integrated into core GIS applications over the coming years.

## 5.3 GEOPHYSICAL DATA PROSSESSING HARDWARE AND SOFTWARE

The vast majority of geophysical data processing that is undertaken is carried out for the hydrocarbon industry which is the sector for which most sub-surface characterisation is undertaken worldwide. As such, most of the software has been designed for optimising data extraction and interpretation in sedimentary environments, but, as more unconventional hydrocarbon resources are explored and developed, this is broadening to include less ‘traditional’ reservoirs including fractured sedimentary and basement rock reservoirs. Commonly, first pass data processing of acquired geophysical data is undertaken by the contractor using their own proprietary software as part of the acquisition contract. Prior to this, data may not be readily portable between systems. Subsequent processing may be undertaken by other specialist organisations or within the hydrocarbon companies own organisation. Software development is usually undertaken in parallel with tool development.

Advances in computing power are continually allowing improvement of the information that may be extracted from the original data. Because the majority of this work is focussed on the hydrocarbon industry, data processing methods are not optimised for other geological environments and ‘calibration’ or development may be required if different formations are being characterised. In particular the interpretation of wireline log and seismic survey information for non-hydrocarbon purposes have always lagged behind however the exploitation of unconventional hydrocarbon resources means that a much broader range of geologies are now examined by that industry.

Data acquisition processing and any modelling associated with preparing the data for use, such as seismic data processing and post flight processing of airborne survey data, is normally undertaken by the acquisition contractor, and the output from any specialist interpretation of such data can normally be input into the systems described above. If this is not the case, the output can be readily converted into formats can used by these and many other applications and it is anticipated that significant software development will not be required to allow data migration for modern geophysical data.

## 5.4 EXPERTISE

Geological mapping and core/cuttings logging will be key geological skills required in the early stages of a site investigation programme. Both of these skills are not unique and are available widely. Because many geoscientists work in the hydrocarbon, water resources and site investigation sectors, they may not have experience of the specific rock types under consideration. However, this issue can be addressed by appropriate on-the-job training as necessary.

Expertise is readily available for operating 3D geological modelling and GIS software with the use of the former widespread in the hydrocarbon industry and the latter in many geosciences sectors and more widely. Similarly, there is expertise in geophysical data processing, though this is largely employed in the hydrocarbon industry and in geophysical companies servicing this industry.

Outside the hydrocarbon sector expertise on the integration and modelling of geological data is more limited, particularly in the context of radioactive waste disposal projects. However, the skills needed do exist and could be attracted to the industry.

While we believe that people with the right types of skills required to undertake this work for a new UK site investigation programme are available, there are two issues that will need to be considered. These are:

- The need to attract people with the necessary skills from other industries may be difficult, particularly from the hydrocarbon sector, where staff are generally well paid;
- Stretching of specialist expertise if two sites are investigated in parallel, especially if spatially close together with similar rocks.

## 5.5 SUMMARY

In terms of resource availability (Objectives 3 and 5 in Section 1.2), the software, hardware and expertise required for the interpretation and geological modelling aspects of a new site characterisation programme in the UK already exist and are widely commercially available. We do not believe that there will be a requirement for the bespoke development of software applications in respect any of the geological environments likely to host a UK repository. Similarly there are no unusual hardware requirements and all necessary hardware is readily available off-the-shelf. While we expect that some training will be required for some of the geological environments and rock types that may be encountered in the new UK programme we believe that there are skilled geoscientists capable of undertaking all of the interpretation and modelling activities that will be required. Attracting appropriate skilled staff from other sectors may be difficult and if two sites with similar geologies are characterised in parallel some specialist areas may be stretched.

# 6 Geological Modelling – Tools for Interpretation and Modelling

This chapter summarises the tools and approaches that have been used by the national radioactive waste disposal programmes reviewed (Chapter 3) and the other sectors considered in Chapter 4. It identifies the tools and methods that have been used in the programmes and sectors reviewed that could be applicable in a new UK site investigation programme. It thus addresses all the objectives identified in Section 1.2 but particularly the final objectives as outlined in Section 1.2 'The extent to which the required resources may vary in response to variations in the geological environment at the site(s) in the UK that are being characterised'; and 'The identification of any gaps in available resources to support a UK-based site characterisation programme'.

In all of the national radioactive waste disposal programmes reviewed in this report the tools and approaches used to develop the geological understanding of the area under consideration have utilised commercially available software and methods developed and widely practised in other sectors. The principal sector for which these have been developed is the hydrocarbon industry where interpretation of geophysical data, including that from wireline logs and VSP surveys, is the main source of information for the development of the geological understanding of an oil field or reservoir and its 3D digital geological modelling are an important consideration. This is supported by 'ground truthing' using non-geophysical information from boreholes and other sources if available. Similar methods are used in the evaluation of coal deposits (whether for exploitation by traditional mining methods, in-situ gasification or coal bed methane extraction), shale gas reserves and for the assessment of potential host rocks for CCS, all of which are occur in similar sedimentary geological environments. One significant difference between these industries, in particular the hydrocarbon, shale gas and CCS, and the radioactive waste site characterisation programmes is that the former frequently use integrated reservoir modelling packages, such as Petrel, Eclipse or Landmark, to undertake detailed analysis of the field while the latter has not as yet adopted this approach.

With one exception, noted below, we are not aware that any bespoke development of modelling or interpretation tools was undertaken on behalf of any of the programmes reviewed in this report for the geological modelling and interpretation of the areas investigated. In all cases software and methods available at the time of the investigations were utilised. It is worth noting that this is not necessarily the case for acquisition and management of the data where several national programmes have developed their own in-house systems from scratch or by modification of existing applications.

## 6.1 SUMMARY OF GEOLOGICAL MODELLING AND INTERPRETATION METHODS AND TOOLS

This section provides a brief overview of the methods and tools used for the geological modelling activities undertaken by the programmes reviewed that are likely to be useful in a new UK site characterisation programme.

### 6.1.1 Mapping (topographical, geomorphological and geological)

All of the programmes running over the last 15 years or so have used standard GIS software for manipulating map based data and its presentation. This is because of the ease of handling this type of data within this environment. Information can readily be exported for use, for example topographic or air photo 'drapes', in 3D models or visualisations.

The Nirex investigations were too early for the use modern GIS and map data was handled in Intergraph software which is a CAD type environment but having some limited GIS capacity. For example, the Reference Drawings prepared for the Nirex public enquiry were created in Intergraph and were made available for use at the inquiry in digital form with a viewer that allowed access to the limited attribute information linked to the maps. The maps were also produced as hard copy prints at two scales (A2 and A0) (Nirex 1995e).

We expect that GIS will be a key tool for the interpretation and interrogation of map (2D geological model) based information. For use in a GIS, data requires information on location but otherwise can handle a wide range of attribute data. ArcGIS and MAPINFO are the most frequently used GIS systems.

### 6.1.2 Geological structure, nature, distribution and properties of rocks

All of the programmes running over the last 20 years or so have used commercially available modelling software for much of the development of their geological models. These include standard hydrocarbon industry packages, such as earthVision and GoCAD (though this was developed by an academic consortium that includes interests outside the hydrocarbon sector), and Vulcan developed for use in the mining industry. Because different 3D geological modelling software packages were originally developed for dealing with specific geological settings and/or for specific industries they were in some cases more suited to the geologies for which they were designed. These differences are now largely no longer apparent and the modelling packages can be used to model all of the geological environments that are likely to be encountered in a UK site investigation programme. Use of integrated packages that are now widely used in the hydrocarbon and related sectors, such as Petrel and Landmark, have not, as far as we are aware, been undertaken by any of the radioactive waste site investigations reviewed here but the use of such software in a forthcoming UK programme is likely to be helpful, especially for sedimentary rock environments. Geological surveys utilise a wide variety of 3D geological modelling and visualisation packages (Section 4.4.2 above provides a summary of these) which include 3D Geomodeller, earthVision, GOCAD, GSI3D, GeoVisionary, Isatis, Petrel, Rockworks, SKUA, Move, Surfer, Surpac and Vulcan.

Where undertaken outside of the digital 3D geological modelling environment development of geological understanding, such as structure contours of rock units, isopacites (thickness contours) and associated activities, has been based on standard CAD drafting software and hand drafting.

### 6.1.3 Spatial heterogeneity

With the exception of the Nirex programme, spatial heterogeneity investigations have utilised commercial approaches to understanding spatial distribution of rock properties. For example, Andra are undertaking an evaluation of the distribution of 'shale' within the potential host rock and porosity distribution in the overlying, more permeable, horizons which, once completed, will be the largest undertaken within the industry covering an area of about 37 $km^2$. This study is being undertaken by an experienced contractor using commercially available software.

The Sellafield spatial heterogeneity (see section 3.1.8) study involved the development of approaches and equations to link acoustic impedance derived from borehole data to that derived from the seismic data in an attempt to populate the 3D seismic volume with rock properties derived from wireline data and core testing. Subsequent review of this work identified a number of problems with the approach used. While such an approach could be adopted in future there are now commercially available methods for this type of data inversion that have been developed for the hydrocarbon industry and are now well tested.

### 6.1.4 Interpretation of structural domains from discontinuity data

Both SKB and Nirex adopted similar approaches to the identification of structural domains from borehole derived discontinuity data. Both used standard statistical approaches to evaluate the distribution and frequency of fracturing to identify volumes of rock with similar fracture characteristics and distributions (which did not necessarily correspond to mapped lithostratigraphic units). Software to undertake the statistical evaluation and for graphically presenting the results is readily available. The expertise and geological understanding required to undertake this type of assessment, in the case of the Sellafield programme, was developed during the earlier phases of work on the programme.

### 6.1.5 Potentially Flowing Feature Logging

As far as the authors are aware from those programmes reviewed here, only for the Sellafield programme has this type of logging has been undertaken although a similar study has been undertaken at Mizunami (Japan). The expertise and understanding required to undertake this type of assessment was developed during the systematic logging of fracture mineralogy in all of the Sellafield (and Dounreay) boreholes supported by detailed laboratory examination of selected fracture mineralisation. This experience allowed the fracture logging team by observation of the cores to interpret which fractures were connected to the groundwater flow network even when such flows were too low to be logged. Software to undertake the statistical evaluation and for graphically presenting the results is readily available.

### 6.1.6 Tectonics

All of the programmes reviewed here have undertaken the monitoring of seismicity in the region around the area of investigation using conventional approaches.

In-situ stress has been determined by borehole break-out studies that are routine in the hydrocarbon industry to interpret stress directions. It has also been determined by overcoring methods to measure magnitude and direction. While this approach is not widely used (it is expensive because of drill rig time) and potentially subject to failure it is not experimental.

### 6.1.7 Geophysical survey interpretation (seismic, non-seismic and wireline)

As far as the authors are aware in all programmes reviewed in this report the interpretation of data from seismic and non-seismic geophysical surveys and wireline data has been undertaken using industry standard software that is readily available. Initial post acquisition processing will normally have been undertaken as part of the acquisition contract and may well use the contractor's proprietary software to process raw data and present acquired data. Subsequent data processing and interpretation has also utilised standard, commercially available software, such as Landmark, for seismic data interpretation.

### 6.1.8 Mining

In addition to re-examination/re-interpretation of mineral exploration (mining and hydrocarbon) which several of the reviewed programmes have undertaken, the Sellafield investigations was the only programme to utilise information interpreted from past mining records and from the mapping of underground workings to provide data to support structural interpretation of the area under investigation. This allowed detailed understanding of fault and fracture patterns and densities to be determined for the cover rocks at an early stage in the investigations from sites close to the area under detailed investigation.

### 6.1.9 Seismic survey interpretation

Seismic data acquisition and interpretation will be a key part of any future UK site investigation programme. It will provide information on the depths and thicknesses of the formations present in an area together with an understanding of their dip and structure, including larger faults (resolution is dependent on a number of factors but faults with throws above about 5m are routinely seismically imaged).

A variety of surface seismic techniques (both 2-D and 3-D) have been employed during the site investigation phase for potential European radioactive waste repository sites. These were aimed at resolving various problems, including mapping the base of the sedimentary cover, mapping faults in the sedimentary cover and in the basement, and investigating examples of potential neotectonic activity. The traditional use of seismic survey data for identifying major faults, and geological structures is the main application in the national programmes reviewed here, and one that has been used with great success. The recent 3D survey by Andra, from which data are still being processed, has been used successfully for identifying small fault structures (with throws down to a few metres) and the geological structure of the target host horizon. The ongoing data interpretation includes inversion to provide at least a qualitative analysis of Callovo-Oxfordian mudstone to assess variability, particularly of the clay content.

Improved computing speeds and technologies mean that processing of the acquired data is quicker and that interpretation of the data is now possible with a higher degree of confidence than has been previously possible in many cases. Re-processing of older data, depending on vintage and quality, in order to extract more information is, in many cases, worthwhile. Several of the programmes reviewed here, notably Sellafield, Bure and Gorleben, undertook re-interpretation of existing, some quite dated, seismic data to develop early understanding of the geological structure of the areas under investigation.

## 6.2 DEVELOPMENTS IN OTHER SECTORS RELEVANT TO A NEW UK PROGRAMME

There are two approaches to interpretation and modelling used in other sectors that have not been used by any of the programmes reviewed here that offer significant potential for developing geological understanding in a new UK site investigation programme. These are the use of high resolution airborne geophysical surveys and the integrated approach to geological mapping and interpretation. Both of these are discussed above (sections 4.4.5 and 4.4.6 respectively).

High resolution airborne geophysical surveys provide high quality high density data that can provide detailed information for the interpretation of sub-surface geology in an area. It is particularly useful where there are concealed rocks with contrasting properties, such as granites (gravity low) or some volcanic rocks (magnetic highs), permitting the interpretation of the distribution and structure of different rock types. Even in areas with a thick succession of sedimentary strata, data from this type of survey is invaluable to guide the interpretation and modelling of the rocks present and their structure.

For the last 10 years the BGS and a few other national geological surveys have been undertaking digital field mapping. By assessing and interpreting existing data prior to and during field mapping the field geologist effectively develops an understanding, at least to a mental conceptual model stage, prior to field work. This is enhanced by pre-field visit visualisation of the data to identify the main uncertainties within and area so that these can be specifically targeted during field work. On-going data assimilation and interpretation during field work ensures that 3D digital geological modelling, usually by the same geologist, that is undertaken on completion of field work is undertaken effectively. The resulting model incorporates new and existing data and the conceptual understanding developed doing the fieldwork which can be validated against the various data sets. If required revisions to the 2D geological map data are made from the 3D model rather than the other way around.

## 6.3 IMPLICATIONS FOR SPECIFIC HOST ROCKS

In broad terms the various techniques discussed in this report and used in the programmes reviewed here are applicable to all of the potential host rocks for a UK repository being considered by RWMD detailed in Chapter 1 above (higher strength rocks with and without sedimentary cover, lower strength sedimentary rocks and evaporites) though they may not necessarily be optimised for them in all cases. Many of the programmes reviewed have been fairly conservative in the methods adopted, for both data acquisition and its subsequent interpretation and geological model development and have utilised technologies that have been developed and widely used in other sectors, primarily the hydrocarbon industry and related sectors.

Some acquisition techniques are better suited to specific rock types, for example seismic surveys do not often image basement or rocks below salt deposits well and some wireline logging methods work better in some rock types than others. Because the hydrocarbon industry is now widely exploring and exploiting ‘unconventional’ resources significant effort has been directed at improving both acquisition and interpretation methods to obtain greater understanding of these environments. For example Controlled Beam Migration of seismic data to better interpret faults in hard rock and basement terrains. As a result the application of tools to the rock types under consideration here will be more useful than previously was the case.

Similarly, advances in the development of 3D geological modelling software means that most of the packages available are now suitable for modelling in sedimentary and hard rock environments.

## 6.4 INTERPRETATION AND MODELLING OF DATA ARISING FROM A UK SITE INVESTIGATION PROGRAMME

The stages of a new site characterisation programme in the UK have been defined in Appendix A of Nirex Report 123 (Nirex 2005). We believe that the described approach is valid and appropriate.

The approaches used by the programmes reviewed here have been based on those that are widespread in other sectors, in particular the hydrocarbon industry and which have been extensively used in the assessment of sites for CCS. We do not believe that development of interpretation or modelling tools will be required for a new UK site characterisation programme and that all the necessary software, hardware and methodologies are currently available to undertake the geological interpretation and modelling required to understand the geology of a site.

While interoperability of data between different platforms and software packages has been challenging in the past we do not believe that this is any longer an issue because most packages now used for modelling and interpretation can readily manage data or models held or created in other packages without difficulty.

The approach that could be adopted to developing the geological understanding of a site is summarised in Table 13 below. We anticipate that the geological understanding of a site, unless it is particularly geologically complex, will be well developed after the third phase noted in this table and that additional phases of data acquisition and subsequent interpretation will only lead to minor modifications to that understanding. As described here these three phases include: a review/reinterpretation of existing information about the site; the acquisition and interpretation of new geological and geophysical information, including geological mapping airborne and ground based non-seismic geophysical surveys; 2D and 3D seismic surveys; and the information derived from the drilling and logging of the first two round of boreholes in order to develop geological understanding and construct digital 3D geological models of the site. We consider one of the principal sources of information for this interpretation is the results of a 3D seismic survey and, therefore, phase 3 described in the table below is only completed once data from such a survey is included in the geological interpretation of the site. The development of similar understanding for superficial (Quaternary) deposits may well be developed semi-independently from that for 'solid' geology but will follow similar phases.

| Phase | Data formats | Activities | Products |
|---|---|---|---|
| 1 - Preliminary assessment | Varied paper and digital formats including point data, borehole logs, geophysical data, structural data geological interpretations etc. from various sources | Assessment, assimilation and interpretation geological data to develop conceptual understanding of the site | First pass 3D geological model of site including understanding of geological evolution and major structure (faults/folds) |
| 2 - New data acquisition | Mainly digital information from new surveys and borehole drilling | Evaluation of new information and revision of conceptual models of the site to honour new data points. | New 3D geological model of site including understanding of geological evolution and detailed structure (faults/folds). Will include more detail than above model. |
| 3 - Further new data acquisition | Mainly digital information from targeted surveys and borehole drilling | Evaluation of new information and revision of conceptual models of the site to honour new data points if necessary. | Revision of 3D geological model of site including understanding of geological evolution and structure (faults/folds). Likely to include some more detail than above model. |
| It is likely that the geology of the site and its evolution will be well understood after three iterations. However further new information may become available as a result of other site investigation activities that are aimed at understanding other aspects of the site that may refine understanding reached during phase 3 meriting a new revision. | | | |

**Table 14** Phases in the development of the geological understanding of a site during site characterisation activities.

## 6.5 SUMMARY

This chapter has described the tools and approaches that have been used by national radioactive waste disposal programmes reviewed (Chapter 3) and the other sectors considered in Chapter 4. It thus addresses all the Objectives as outlined in Section 1.2 but specifically Objectives 4 and 5. Broadly, all reviewed national radioactive waste programmes have utilised methods and software developed in other sections, principally the hydrocarbon industry, for geological interpretation and modelling. There are new methods of interpretation currently being developed which have not been used in reviewed national programmes e.g. 3D digital mapping, and which, we believe, would enhance the geological understanding in a future UK site investigation programme. However, we believe that all the necessary software, hardware and methodologies necessary for a future programme are currently available.

# 7 Conclusions

This report has achieved the objectives stated in Section 1.2 above to provide an account of:

1. The processes and tools that have been used on international radioactive waste management programmes for processing, interpreting and modelling the data acquired through site characterisation;
2. Any additional processes and tools that are used in other sectors for processing, interpreting and modelling data acquired through site characterisation that may be applicable to a UK-based waste management site characterisation programme.
3. The availability of resources (tools and specialist practitioners) for undertaking such a programme of processing, modelling and interpretation in the UK;
4. The extent to which the required resources may vary in response to variations in the geological environment at the site(s) in the UK that are being characterised; and
5. The identification of any gaps in available resources to support a UK-based site characterisation programme.

## 7.1 MAIN CONCLUSIONS

1. A variety of national programmes with broad selection of geological settings were chosen for this review, including: Basement without cover (Sweden (SKB), Finland (Posiva) and Switzerland (Nagra)); Basement with cover (UK (Nirex)); Low permeability sedimentary rocks (France (Andra) and Switzerland (Nagra)); Bedded salt (USA (WIPP)); and Salt dome (Germany). The programmes were selected because they have examined geological settings suitable for the siting of a repository that are relevant to the geology of the UK; i.e. similar geological situations may be examined by the British repository programme. These programmes were reviewed in enough detail to describe the approaches used to develop the geological understanding of the areas investigated

2. An account of the examples reviewed here from the national programmes illustrate the development of techniques, data handling and interpretation and geological model development in different national programmes (as specified in the first objective in Section 2.1). Most specific techniques to obtain geological data are common to all the examples e.g. surface geophysics, seismic surveys, use of geological information from boreholes. The level of sophistication in interpreting the information so that it can be used in geological site models appears to be a function of the complexity of the geological setting and when the programme was operational. For example, the Nirex Sellafield example is a good illustration of practice in the 1990s for preliminary site selection in a complex geological setting. The Swedish and Finnish programme examples are more recent, albeit with a relatively less complex geological setting, and show how the development of a site description models can be used iteratively to move from a regional scale geological model to a site model for a ‘hard’ rock site.

3. Analysis of additional processes and tools that are used for site characterisation in other industries (as specified in the second objective in Section 1.2) shows that for many sectors, including carbon capture and storage and hydrocarbon exploration work, the interpretation and modelling of geological information is critical and is primarily focussed on the specific needs of that particular sector. Nevertheless, standard industry products and practices are available for the baseline geophysical analysis and interpretation. Other more specific software packages are needed for more

sophisticated modelling of such data. These are largely based on those used in the hydrocarbon industry and it is this sector that historically has driven new developments in data acquisition, processing and interpretation methods and techniques. There are a range of commercial 3D digital geological modelling and GIS packages readily available capable of fully supporting the development of geological site descriptive models for all of the geological environments likely to be examined during a new site investigation programme in the UK.

4. In terms of resource availability (Objectives 3 and 5 in Section 1.2), the software, hardware and expertise required for the interpretation and geological modelling aspects of a new site characterisation programme in the UK already exist and are widely commercially available. We do not believe that there will be a requirement for the bespoke development of software applications in respect of any of the geological environments likely to host a UK repository. Similarly there are no unusual hardware requirements and all necessary hardware is readily available off-the-shelf. While we expect that some training will be required for some of the geological environments and rock types that may be encountered in the new UK programme we believe that there are skilled geoscientists capable of undertaking all of the interpretation and modelling activities that will be required. Attracting appropriate skilled staff from other sectors may be difficult. If two sites with similar geologies are characterised in parallel it is possible that some specialist areas may be stretched unless appropriately scheduled.

5. With regard to use of tools for geological modelling (Objectives 4 and 5), broadly, all reviewed national radioactive waste programmes have utilised methods and software developed in other sections, principally the hydrocarbon industry, for geological interpretation and modelling. There are also now new approaches which have not been used in the reviewed national programmes e.g. integrated 3D digital mapping, and which, we believe, would enhance the geological understanding in a future UK site investigation programme if used. However, we believe that all the necessary software, hardware and methodologies necessary for a future programme are currently readily available.

# 8 References


Akhurst, M V, Chadwick, R A, Holliday, D W, McCormac, M, McMillan, A A, Millward, D, and Young, B. 1997 Geology of the West Cumbria District. *Memoir of the British Geological Survey*, Sheet 28, 37 and 47 (England and Wales).

Andra 2005a Dossier Argile – Synthesis - Evaluation of the feasibility of a geological repository in an argillaceous formation Meuse/Haute-Marne site *Andra Report Series* and supporting volumes

Andra 2005b Dossier Granite – Synthesis - Assets of granite formations for deep geological disposal *Andra Report Series* and supporting volumes

Arthur, J. and Associates 1991. New geophysical data - Sellafield. Report to UK Nirex.

Arthur, J. and Associates 1992. Sellafield Transition Zone Survey. Report to UK Nirex.

Barnes, R.P., Hughes, R.A. and Petterson, M.G. 1991a. A revised geological map (solid) of the Sellafield District. British Geological Survey Technical Report WA/91/36C.

Beamish, D. and White, J.C., 2011. A radiometric airborne geophysical survey of the Isle of Wight. Proceedings of the Geologists' Association, 122 (5). 787-799.

Berg, R.C., S.J. Mathers, H. Kessler, D.A. Keefer (Eds), 2011. Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations. Illinois State Geological Survey Circular 578, Champaign, Illinois, 92p.

Birkhäuser, P.H., Roth, P.H., Meier, B. and Naef, H. 2001. 3D-Seismik: Räumliche Erkundung der mesozoischen Sedimentschichten im Zürcher Weinland. TECHNISCHER BERICHT 00-03.

BMWi, 2008, Final Disposal of High-level Radioactive Waste in Germany - The Gorleben Repository Project; Federal Ministry of Economics and Technology (BMWi); 67p.

Bornemann, O., Behlau, J., Mingerzahn, G. and Schramm, M. 2002. Project Gorleben – Geologische Bearbeitung der Schachte Gorleben 1 und 2 (Hutgestein uns Salinar). Abschlussbericht. – BGR, upubl. Report: 159 pp., 17 Fig., 12 Tab., 28 Apps., 16 ATT.; Hannover.

Bornemann, O. Behlau, J., Fischbeck, R, Hammer, J. Jaritz, W, Keller, S., Gerhard Mingerzahn, G., Schramm, M. 2008. Description of the Gorleben Site, Part 3: Results of the geological surface and underground exploration of the salt formation. BGR report. 223 pp.

Borns, D.J. 1997. History of geophysical studies at the waste isolation pilot plant (WIPP), southeastern New Mexico.

Bräur, V. and 13 others., 2011. Description of the Gorleben Site, Part 4, Geotechnical exploration of the Gorleben salt dome. BGR report.176 pp.

Brodie, R.C. and Sambridge, M., 2006. A holistic approach to inversion of frequency-domain airborne EM data. Geophysics, 71, G301-G312.

Chadwick, RA, Evans, DJ, Wingfield, RTR, Hulbert, AG and Holliday, DW 1992 An interpretation of regional seismic reflection data offshore Sellafield. BGS Technical Report WA/91/56C, Nirex Report 270.

Chadwick, R.A. and Holliday, D.W. 1988. Stratigraphy and structure of the Sellafield area from new seismic reflection data. Rep. Deep Geol. Res. Gp. Brit. Geol. Surv., 88/9.

CHADWICK, R A, ARTS, R, BERNSTONE, C, MAY, F, THIBEAU, S, and ZWEIGEL, P. 2008. Best practice for the storage of CO2 in saline aquifers. (Keyworth, Nottingham: British Geological Survey Occasional Publication No. 14).

Curtis, P; Elfström, M; and Markström, I; 2005 Rock Visualization System Technical description (RVS version 3.8), SKB Technical Report R-05-49, Svensk Kärnbränslehantering AB.

DOE (U.S. Department of Energy), 1997b. Waste isolation plant disposal phase: Final Supplemental Environmental Impact Statement, Volume 1, Chapters 1-6, September, Carlsbad, New Mexico.

Eaton, GP, 1993; Quaternary Geology of the Sellafield Area : Interim Assessment; Nirex Report 519.

Emsley, S., 2008. Geosphere Characterisation Project : Data Acquisition Report Surface : Surface Based Geophysical Techniques. NDA Report Number 07154270359.501.

Emsley, S., 2010. Site Characterisation Programme: Report on the Inversion of Multiple Geophysical data. NDA Report Number 10514270103.500/A.0.

Evans, C.J., Cuss, R.J. and Kingdon, A. 2002. Wireline Geophysical Logging of the Nirex Deep Borehole in the Sellafield Area: Review of the Status of Wireline Logs and Their Use to Measure Porosity. British Geological Survey Commissioned Report, CR/02/166. 32pp.

GDGG (Gibb Deep Geology Group) 1994 Manual of Geological Logging Methods Issue 3 Rev 0 Doc ref GIBB/92127A/TR/025.

Geoscience Limited, 1991. Sellafield Site-District Geology JIT, Phase 1 Interpretation, Data Integration. Report to UK Nirex.

Geoscience Limited, 1992. Remote Sensing Studies of the Sellafield Region. Report to UK Nirex.

Hunter, J and Shaw, R. P. 2011 The Cressbrook Dale Lava and Litton Tuff, between Longstone and Hucklow Edges, Derbyshire; Mercian Geologist; Vol 17; No 4; pp 229-242.

Jaritz, W. 1973. Zur Entstehung der Salztruckturen Nordwestdeutschlands. Geol. Jb. A 10, 1-77.

Jaritz, W. 1994. Die Entwiicklungsgeschichte des Standortes als naturliches Analogon fur das Langzeitverhalten eines Barrierensystems. Z.dt. geolGes., 145/1:192-206, Hannover.

Köthe, A., Hofmann, N., Krull, P., Zirngast., M., Zwirner., R. 2007. Description of the Gorleben Site Part 2: The Geology of the Overburden and Adjoining Rock of the Gorleben Salt Dome, Germany. BGR Report, Hannover, 192 pp.

Kuhlman, K.L. and K.S. Barnhart, 2011, Hydrogeology Associated with the Waste Isolation Pilot Plant. American Nuclear Society, Albuquerque, NM, International High-Level Radioactive Waste Management Conference, paper 3317. (7pp)

Lappin, A. R. and Hunter R. L. (editors). 1989, Systems analysis, long term radionuclide transport, and dose assessment, Waste Isolation Pilot Plant (WIPP), southeastern New Mexico, Sandia Report, SAND89-0462. Sandia National Laboratories, Albuquerque NM.

Lahdenperä, A-M., Palmén, J. and Hellä, P. 2005. Summary of Overburden Studies at Olkiluoto with an emphasis on Geosphere-Biosphere Interface. Posiva Oy, Working Report.

LI, E. 1998. Processing pp and ps waves in multicomponent sea-floor data for azimuthal anisotropy: theory and overview. Revue de L'Institut Français du Pétrole , Vol. 53 (5)

LIU, E, MAULTZSCH, S, CHAPMAN, M, LI, X Y, QUEEN, J H and ZHANG, Z. 2003. Frequency-dependent seismic anisotropy and its implication for estimating fracture size in low porosity reservoirs. The Leading Edge, Vol .22, 662-665

MCKENNA, J J, GUREVICH, B, URESOVIC, M, and EVANS, B J, 2003. Rock physics – application to geological storage of CO2. Unpublished PhD Thesis, Curtin University of Technology.

Milowdowski, AE, Fortey, NJ, Gillespie, MR, Pearce, JM and Hyslop, EK 1998 Synthesis report on the mineralogical characteristics of fractures from the Nirex boreholes in the Sellafield area, BGS Technical Report WG/98/8.

MRWS 2008 Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal UK Government White Paper Command 7386.

Nagra 1985a, NGB 85-01 to 85-08 Report series on Project Gewähr. *Nagra Gewähr Bericht NGB 88-01 to 08. Nagra, Wettingen, Switzerland.*

Nagra 1985b, NGB 85-09 Project Gewähr 1985 Nuclear waste management in Switzerland: Feasability studies and safety analyses (English overview) *Nagra Gewähr Bericht NGB 88-09 Nagra, Wettingen, Switzerland.*

Nagra 1988, NTB 88-25 Sediment Study – Disposal options for long-lived radioactive waste in Swiss sedimentary formations – Executive summary *Nagra Technischer Bericht NTB 88-25 Nagra, Wettingen, Switzerland.*

Nagra 1994a, NTB 93-09E Kristallin-I – Conclusions from the regional investigation programme for siting a HLW respository in the crystalline basement of Northern Switzerland *Nagra Technischer Bericht NTB 93-09E Nagra, Wettingen, Switzerland.*

Nagra 1994c NTB 94-14 Interpretation der Reflexionsseismik im Gebiet nördlich Lägeren-Zürcher Weinland *Nagra Technischer Bericht NTB 94-14 Nagra, Wettingen, Switzerland.*

Nagra 1994d NTB 94-10 Sedimentstudie Zwischenbericht 1993 Zusammenfassende Übersicht der Arbeiten von 1990 bis 1994 und Konzept für weitere Untersuchungen *Nagra Technischer Bericht NTB 94-10 Nagra, Wettingen, Switzerland.*

Nagra 2000a NTB 00-03 3D-Seismik: Räumliche Erkundung der mesozoischen Sedimentschichten im Zürcher Weinland *Nagra Technischer Bericht NTB 00-03 Nagra, Wettingen, Switzerland.*

Nagra, 2000b 3D seismics in the Zürcher Weinland *Nagra Bulletin 33, Nagra, Wettingen, Switzerland.*

Nagra 2002c. NTB 02-05 Project Opalinus Clay Safety Report "Demonstration of Disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate level waste (Entsorgungsnachweis)" *Nagra Technischer Bericht NTB 02-05 Nagra, Wettingen, Switzerland.*

Nagra 2009 NTB 09-06 The Nagra Research, Development and Demonstration (RDandD) Plan for the Disposal of Radioactive Waste in Switzerland. *Nagra Technischer Bericht NTB 09-06, Nagra 2009 Wettingen, Switzerland.*

NDA 2010, Site characterisation for a geological disposal facility, Status report March 2010. Report No NDA/RWMD/057.

Nirex 1993a The Geological Structure of the Sellafield Area: December 1993 Update. Nirex Report 520

Nirex 1993b The Geology and Hydrogeology of the Sellafield Area, Nirex report 524

Nirex 1995a The 3D Geological Structure of the PRZ. Nirex Report SA/95/026

Nirex 1995b Flow-Zone Characterization: Mineralogical and Fracture Orientation Characteristics in the PRZ and Fleming Hall Fault Zone Area Boreholes, Sellafield, Nirex Report SA/95/001

Nirex 1995c Preliminary Analysis of the Groundwater Pathway for a Deep Repository at Sellafield. Nirex Report S/95/012 (3 volumes).

Nirex 1995d, The 3D Geological Structure of the PRZ, Nirex Report S/95/005.

Nirex 1995e, Sellafield Geological and Hydrogeological Investigations. Factual Report - Compilations of Maps and Drawings, Nirex Report SA/95/002. 2 volumes

Nirex 1995f, Sellafield Seismological Database, Nirex Report SA/95/003

Nirex 1996 Structural Atlas of the Sellafield Boreholes; Nirex Report SA/96/005

NIREX 1997a Sellafield Geological and Hydrogeological Investigations: The Geological Structure of the Sellafield Site. Science Report No. S/97/007. UK Nirex Ltd, Harwell, Oxfordshire

Nirex 1997b The 3D Structure of the Sellafield Site. Nirex Report SA/97/027

Nirex, 1997c, Quaternary Evolution of the Sellafield Area; Nirex Report SA/97/002; 60p.

Nirex 1997d Spatial Heterogeneity of the Rock Mass within the Potential Repository Zone, Nirex Report S/97/005; 48p

Nirex 1997e The lithological and discontinuity characteristics of the Borrowdale Volcanic Group at outcrop in the Craghouse Park and Latterbarrow areas; Nirex Report SA/97/029.

Nirex 1997f Spatial Heterogeneity of Rock Mass Properties, Nirex Report SA/97/021

Nirex 1997g Generation of a new digital terrain model for the Sellafield area, Nirex Report SA/97/067

Nirex 1997h Sellafield Geological and Hydrogeological Investigations: The Geological Structure of the Sellafield Site, Nirex Report S/97/007.

Nirex 1997i, Sellafield Geological and Hydrogeological Investigations: Assessment of the In-Situ Stress Field at Sellafield, Nirex Report S/97/003.

Nirex 1997j The lithological and discontinuity characteristics of the Borrowdale Volcanic Group at outcrop in the Craghouse and Latterbarrow areas, Nirex report SA/97/029

Nirex 1997k Phase 1A of the Rock Characterisation Facility Geological Model Development: Gross RCF Predictions, Nirex Report SA/97/068

Nirex, 2005, Geosphere Characterisation Project: Status Report: Nirex Report No. N/123, UK Nirex Ltd, Harwell, Oxfordshire.

Petersson J, Skogsmo, G, Berglund, J and Stråhle, A, 2006, Oskarshamn site investigation - Comparative geological logging with the Boremap system: 9.6–132.2 m of borehole KLX07B, SKB Report P-06-82.

Posiva Oy, 2009. Okliluoto Site Description 2008 Part 1 and 2. Posiva Report 2009-01. Assessment Report: General Summary (in English). Posiva OY, Helsinki, Finland.

Powers, D. W., Lambert, **S.** J., Shaffer S.E., Hill. R.E. and Weart, W. D. (editors). 1978, Geological characterisation report, Waste Isolation Pilot Plant (WIPP) site, southeastern New Mexico, Sandia Report. SAND78-1596. vol. 1-2, Sandia National Laboratories, Albuquerque NM.

Rogers, SF, 1994; FMS/BHTV Derived data for Sellafield BH2-7. Core Characterisation Programme Report No. CC94S/471/CF-1-A. Nirex report No. 540.

Rogers, SF, and Shaw, RP, 1993; Correction of Drillers Depths to FMS/FMI Depths for Sellafield Boreholes 2, 3, 4, 5, 7A and 7B. Core Characterisation Programme Report No. CC93S/239/IF-B-C.

ROSS, C P. 2002. Comparison of popular AVO attributes, AVO inversion, and calibrated AVO predictions. The Leading Edge, Vol. 21, 244-252

Sanford, A., K. Lin, and L. Jaksha, 1995, *A Report on the Seismicity of the WIPP Site for the Period April 1, 1995 Through June 30, 1995,* WD:95:02158, Westinghouse Electric Corporation, Carlsbad, New Mexico.

Schmelzbach, C. and Juhlin, C. 2004. Oskarshamn site investigation: 3D processing of reflection seismic data acquired within and near the array close to KAV04A on Ävrö. Report P-04-204. Swedish Nuclear Fuel and Waste Management Company.

Shaw, RP 1994 UK Nirex Ltd. Off-site Core Characterisation Programme: Examination, Testing and Analysis of Borehole Cores. Core Characterisation Programme report No. CC94G/391/IF-A-C

SKB, 2002a. Forsmark – site descriptive model version 0. SKB R-02-32, Svensk Kärnbränslehantering AB.

SKB, 2004a. Preliminary site description Simpevarp area – version 1.1. SKB R-04-25, Svensk Kärnbränslehantering AB.

SKB, 2004b. Preliminary site description Forsmark area–version 1.1. SKB R-04-15, Svensk Kärnbränslehantering AB.

SKB, 2005a. Preliminary site description. Simpevarp subarea – version 1.2. SKB R-05-08, Svensk Kärnbränslehantering AB.

SKB, 2005b Hydrogeochemical evaluation. Preliminary site description Forsmark area –version 1.2. SKB R-05-17, Svensk Kärnbränslehantering AB.

SKB, 2005c Preliminary site description Forsmark area – version 1.2. SKB R-05-18, Svensk Kärnbränslehantering AB.

SKB, 2005d. Forsmark site investigation. Programme for further investigations of geosphere and biosphere. SKB Technical Report R-05-14, Svensk Kärnbränslehantering AB.

SKB, 2006a. Preliminary site description. Laxemar subarea – version 1.2. SKB R-06-10, Svensk Kärnbränslehantering AB.

SKB, 2006b. Preliminary site description Laxemar stage 2.1. Feedback for completion of the siteinvestigation including input from safety assessment and repository engineering. SKB R-06-110, Svensk Kärnbränslehantering AB

SKB, 2007. Site descriptive modelling Forsmark, stage 2.2. A fracture domain concept as a basis for the statistical modelling of fractures and minor deformation zones, and interdisciplinary coordination SKB Report R-07-15.

SKB, 2008 Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. SKB TR-08-05. Svensk Kärnbränslehantering AB.

SKB, 2009. Site description of Laxemar at completion of the site investigation phase. SDM-Site Laxemar. SKB report TR-09-01, Svensk Kärnbränslehantering AB

Smith, IF; 2005 Digital Geoscience Spatial Model Project Final Report; BGS Occasional Publication No. 9; 56p.

STEWART, R R, GAISER, J E, BROWN, R J, and LAWTON, D C. 2003. Converted-wave seismic exploration: Applications. Geophysics , Vol. 68, 40.

Uranium Institute 2000 World-wide Advances in Radioactive Waste Management: July 1999 - July 2000. *A report of the Uranium Institute Waste Management and Decommissioning Working Group. Knightsbridge, London.*

Vaittinen, T., Saksa, P., Nummela, J., Palmén, J., Hellä, P., Ahokas, H. and Keskinen, J. 2001. Bedrock model of Olkiluoto site, revision 2001/1 (in Finnish with an English abstract). Helsinki, Finland: Posiva Oy. 190 p. Working Report 2001-32.

Vira, J. 1995 Disposal of high-level radioactive waste in Finland. 87-94 in *Geological Problems in Radioactive Waste Isolation. Second Worldwide Review. Rept. LBNL-38915, Earth Sciences Division, Ernest Orlando - Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA.*

White, JC and Beamish, D.,. 2010. The HiRES airborne geophysical survey of Anglesey: Processing Report. British Geological Survey Internal Report, OR/10/002. 44pp.

WILSON, M, and MONEA, M. 2004. IEA GHG Weyburn CO2 Monitoring and Storage Operation Summary Report 2000-2004. (Regina: Petroleum Technology Research Centre).

Vinje, V, Roberts, G and Taylor, R, 2008 Controlled beam migration: a versatile structural imaging tool; First Break (EAGE) Volume, pp 109-113.

YJT 1992a Final Disposal of Spent Fuel in Finnish Bedrock: Technical Plans and Safety Assessment. *Report YJT-92-31E, Nuclear Waste Disposal Commission of Finnish Power Companies, Helsinki, Finland.*

Zirngast, M. 1991. Die Entwicklungsgeschichte des Salzstocks Gorleben – Ergebnisse einer struktureologischen Bearbeitung. Geol. Jb., A.132: 3-31. Hannover

Zirngast, M., Zwirner, R., Bornemann, O., Fleig, S., Hoffmann, N., Kothe, A., Krull, P. And Weiss, W.2003. Projekt Gorleben. Schischtenfolge und Strukturbau des Deck – u. Nebengebirges. Abschlussbericht, BGR, upubl. Report, 565 pp. Hanover.