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UNITED KINGDOM NIREX LIMITED
Rock Characterisation Facility
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PROOF OF EVIDENCE
OF
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GEOLOGY AND HYDROGEOLOGY

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DR ROBERT CHAPLOW will say:

1. PERSONAL DETAILS

1.1 I have been the Manager for Site Characterisation in the Science Department of United Kingdom Nirex Limited ('Nirex') since June 1993. I am responsible for acquiring and interpreting site specific data in the Sellafield area in order to understand and describe the geology and hydrogeology as an input to the assessment of the suitability of the site for development of a deep repository for radioactive waste disposal.

1.2 I hold a first class honours degree in Geology of the University of London and am an Associate of the Royal School of Mines, London. Following post graduate research I was awarded a Doctor of Philosophy degree by London University and a Diploma of Membership of the Imperial College. I am a Fellow of the Geological Society of London and a Chartered Geologist. I was a Lecturer in Engineering Geology at Imperial College (1971-75) and external examiner for the MSc course in Engineering Geology at Leeds University (1989-92). I have been a member of the Programme Board of the British Geological Survey (1988-93), a member of the Universities Funding Council Research Assessment Review Panel for Earth Sciences and Environmental Studies (1992), a member of the Natural Environment Research Council's Earth Science Committee (1993-94) and of their Earth Science and Technology Board (1994 to date). I was appointed by the Minister for the Environment and Countryside as a Member of Council of the Nature Conservancy Council for England (English Nature) and served in this position from 1991-95. I am the author of 17 technical papers on aspects of geology and hydrogeology and have presented papers at technical conferences and seminars in UK, India, Thailand and the United States.

1.3 From 1975 until I joined Nirex in 1993 I was employed by Sir Alexander Gibb & Partners, initially as Chief Engineering Geologist. I was appointed as an Associate of the company in 1985 and a Director in 1989. I have been responsible for providing geological and hydrogeological inputs to the investigation, design and construction of over 50 major engineering projects located in more than 30 countries world-wide. These projects have included tunnels, major underground openings and dams. I was Project Manager for the work undertaken by Gibb for Nirex for the characterisation of the site at Fulbeck as a potential site for shallow disposal of radioactive waste, and was Project Director for the work undertaken to investigate the sites at Dounreay and Sellafield. On behalf of Nirex I managed the first phase of geological and hydrogeological interpretation of the geological and hydrogeological data from Dounreay and Sellafield in 1991/92 which led to the issues of Nirex Reports 263 to 272 on Sellafield in 1992 and to the preparation of the reports on Dounreay which were subsequently issued as Nirex Reports 653, and 657 to 661.

2. SUMMARY

Scope of the Evidence

2.1 My evidence summarises and interprets the results available so far from studies and surveys of the geology and hydrogeology of the Sellafield site.

2.2 Reference is made to two reports, published by Nirex, that summarise the results. These are *Nirex Report 524* [COR/517] published in 1993, and *Nirex Report SA/95/002* [COR/518], published in 1995. Information is given on sources of unpublished data which are available for reference.

2.3 My evidence describes:

i. the investigations carried out so far;

ii. the geological structure of the Sellafield site to provide the framework for the description of the conclusions from the investigations; and

iii. our understanding of the characteristics of the site in relation to the three key areas of uncertainty to be addressed by the Rock Characterisation Facility ('RCF'):

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

2.4 Separate sections present, for each of these three areas of uncertainty, the current understanding and the remaining uncertainties which need to be resolved. Those issues that cannot be resolved from the surface and must be addressed from underground in the RCF are highlighted.

Investigations So Far

2.5 Nirex has carried out an extensive and systematic investigation of the geology and hydrogeology of the Sellafield site using a range of surface-based

techniques. A wide range of technical specialists has conducted the work and care has been taken to avoid undue reliance on any single technique in the interpretation of ground conditions.

2.6 The investigations have been carried out primarily within an area some 60 km by 65 km, centred on Sellafield and have comprised:

i. drilling at twenty two sites with a total of 25,712 metres of drilling. The deepest borehole is 1,950 metres deep. Most of the drilling has been carried out to obtain continuous core of the rock penetrated;

ii. hydrogeological testing, groundwater sampling, geophysical surveys and the installation of instruments to monitor groundwater conditions in the boreholes; and

iii. geological mapping, hydrogeological and geophysical surveys and earthquake monitoring, all carried out from the surface.

2.7 Carrying out investigation and construction activities at the site perturbs the groundwater pressures and can perturb the geochemical characteristics of the groundwater. The results so far show that baseline hydrogeological conditions have been established.

Geological Structure

2.8 The geological structure of the site has been defined by the investigations carried out. Detailed maps and sections showing the distribution of the main geological units and the faults that cut them have been published (*Nirex Report 524* [COR/517] *and Nirex Report SA/95/002* [COR/518]).

2.9 The Borrowdale Volcanic Group of rocks ('BVG'), the potential repository host rocks, crops out (is at the surface) in the east of the Site area. Towards the west, the BVG is overlain by a sequence of cover rocks. These comprise Triassic sandstones (Ormskirk Sandstone, Calder Sandstone and St. Bees Sandstone) and a group of Permian rocks designated the 'Cumbrian Coast Group'.

2.10 The rocks are cut by a series of faults that displace the rock units. In the onshore area, these faults generally trend in a north-west to south-east direction. Other fault directions do occur, the most notable of which are the east-north-east to west-south-west trend shown by the faults in the Seascale Fault Zone.

2.11 The geological structure of the Potential Repository Zone ('PRZ') has been defined in greater detail than the surrounding area as a result of the greater concentration of investigations carried out in the area. The BVG has been sub-divided into a series of formations and members having distinct geological and hydrogeological characteristics. Further investigations are in progress, most notably the interpretation of a 3-D seismic reflection survey, that will further assist in extending this detailed interpretation across the wider PRZ.

Groundwater Flow and Radionuclide Transport

2.12 The main way in which radionuclides can be transported away from a repository is by flow of groundwater. The groundwater flow through the rocks

is thus an important factor in determining the performance of a repository in terms of its ability to limit releases of radioactivity.

2.13 With reference to an extensive range of hydrogeological and geochemical data, it is shown that groundwater flow in and through the BVG is low. This conclusion is based on the following observations:

i. the hydraulic conductivity of the BVG is low;

ii. groundwater flow through the BVG is through fractures in the rock;

iii. groundwater flow in and through the BVG is controlled by the flowing fractures, which comprise around 0.5% of the fractures in the BVG;

iv. the network of flowing fractures was largely created some 200 million years ago and has persisted since that time, although changes to individual flowing fractures are likely to have occurred. The persistence of the network indicates a high degree of stability within the system;

v. significant progress has been made in establishing the geological characteristics of the flowing fractures thus providing confidence regarding extrapolation of conditions through the rock mass;

vi. the flowing fractures are linked to form networks of connected fractures through which groundwater can flow. This was deduced initially from the results of the short-term hydrogeological testing. Testing carried out during the last eighteen months, particularly the Fracture Network Testing, Cross-Hole Hydraulic Testing and the Borehole RCF3 Pump Test, has indicated that these connections may not be as extensive as had been originally inferred;

vii. a provisional conclusion from the Borehole RCF3 pump test is that there appears to be little connection between the BVG and the overlying sandstones;

viii. there is little or no vertical component of environmental head gradient from the likely level of a repository through to the base of the Brockram and, in some parts of the PRZ, on up into the sandstones; and

ix. the geochemical data, and particularly the conclusions on long residence times, are providing independent confirmation of low groundwater flow.

2.14 Dilution of any groundwater leaving a repository located at depth in the BVG is provided largely by a combination of low groundwater flows in the BVG and mixing of this water with higher flows shown to be occurring in the overlying sandstones.

2.15 However, the surface-based investigations have not been able fully to address the remaining uncertainties due to the inherent limitations of measurements made in boreholes drilled from the surface. Firstly, the boreholes are only able to sample the rock over a limited volume defined by the length (or depth) of the hole and its diameter. Many features, such as fractures, are thus inadequately sampled. Secondly, the borehole testing is unable to provide direct evidence concerning the spatial variability and length of the fractures, or of the ways in which they form networks of connected flowing fractures. Limited indirect evidence is, however, provided by the various forms of hydrogeological testing carried out in the boreholes.

2.16 It is the characterisation of the flowing fractures and, in particular, the way in which these are connected so as to permit the movement of groundwater

through the BVG and into overlying strata, that constitutes the principal area of remaining uncertainty.

Natural and Induced Changes to the Geological Barrier

2.17 It is important to be able to demonstrate that future change, which may be natural or induced by repository construction, will not create new pathways that would result in unacceptable groundwater flows or cause damage to the engineered barriers of the repository that would significantly impair their ability to retain radioactivity.

2.18 Studies related to natural and induced changes to the geological barrier have concluded that:

i. the Sellafield Region area, like most basement areas, owes its origins to a long geological history. At Sellafield this history can be traced back some 460 million years. The geological structure has been defined by the investigations;

ii. dating of fault rocks and studies of fracture mineralisation support the view that the last major episode of faulting occurred over 100 million years ago and that the flowing fractures are part of a system of fractures that has probably persisted in the rocks for around 200 million years;

iii. no evidence has been found of tectonic faults having involved both bedrock and the Quaternary deposits nor has any evidence been found to indicate that there has been extensive flushing of the water from depth within the BVG during the last glaciation;

iv. earthquake activity in the UK is low and is not expected to have a significant effect on the physical stability of the site in terms of its potential to host a repository;

v. construction of underground openings will cause excavation disturbance. The likely extent of this disturbance has been estimated using mathematical models based on data obtained from the surface-based investigations; and

vi. measurements underground in the RCF are needed to address remaining uncertainties regarding the changes which may be caused to fractures in the rock at depth and measurement of excavation disturbance.

Design and Construction of the Repository

2.19 If a repository is constructed at the site, decisions will be needed to select the depth, location, layout and orientation of the repository vaults. This selection will be influenced by the nature, distribution and dimensions of potentially important structures within the rock mass that could control rock quality or groundwater flow.

2.20 Studies related to the design and construction of a repository have concluded that:

i. the BVG is variable. A relationship has been established between identified rock units, the characteristics of the fractures, the occurrence of flow zones, and between flow zone hydraulic conductivity and depth; and

ii. uncertainties over the characteristics of the network of connected flowing fractures need to be resolved and can only be addressed through investigations carried out underground in the RCF.

Conclusions

2.21 Nirex has carried out an extensive and systematic investigation of the geology and hydrogeology of the Sellafield site using a wide range of techniques and technical specialists. So far the investigations have been carried out entirely from the surface.

2.22 Studies of the geology of the area have confirmed that the geological sequence and structure are essentially as was expected when the decision was taken in 1989 to investigate the site. The investigations have, however, added substantial detail to the understanding of the geology.

2.23 Recognising that the main way in which radionuclides can be transported away from a repository is by flow of groundwater, considerable effort has been directed towards understanding the hydrogeology of the site. In my opinion, the studies have confirmed that the site has the two main characteristics favourable for locating a repository. Firstly, there are low groundwater flows in the BVG which would host the repository and, secondly, there would be substantial subsequent dilution of any solutes in that water as it joins the active groundwater system in the overlying sandstones.

2.24 These favourable characteristics of the site are being indicated by a range of independent observations. Thus, the likely low groundwater flows are being indicated by measurements of low hydraulic conductivity in the BVG, by observations that flow is through a small sub-set of fractures, and by observations of groundwater chemistry that indicate residence times for water and solutes in the BVG of possibly up to 1.5 million years.

2.25 A provisional conclusion from the Borehole RCF3 Pump Test is that there appears to be little connection between the BVG and the overlying sandstones.

2.26 The groundwater system at the site is increasingly well understood and capable of being described using simple mathematical models supported by a number of independent datasets. Good progress is being made in matching the predictions from these models with independent field measurements.

2.27 However, the surface-based investigations are not able fully to address the remaining uncertainties due to the inherent limitations of measurements made in deep boreholes drilled from the surface. Firstly, the boreholes are only able to sample the rock over a limited volume defined by the length (or depth) of

the hole and its diameter. Many features, such as fractures, are thus inadequately sampled. Secondly, the borehole testing is unable to provide direct evidence concerning the spatial variability and length of the fractures and of the ways they form the networks of connected fractures that control groundwater flow.

2.28 It is the characterisation of the flow zones and, in particular, the way in which these form networks of connected fractures so as to permit the movement of groundwater through the BVG and into overlying strata, that constitutes the principal area of remaining uncertainty.

2.29 Uncertainties also exist regarding the extent to which current models reliably predict excavation disturbance and the variations in rock properties as they impact the selection of the depth, location, layout and orientation of the repository vaults.

2.30 These remaining uncertainties need to be addressed before a decision can be made to propose a repository at the site. They can only be addressed through investigations in the RCF.

3. SCOPE OF THE EVIDENCE

3.1 My evidence summarises and interprets the results available so far from studies and surveys of the geology and hydrogeology of the Sellafield site.

Documentation

3.2 The results of the investigations so far carried out at Sellafield are contained in reports and appendices comprising over 1600 individual volumes. The document structure is summarised in Table 3.1. This shows the various categories of reports which contain the results. In order to assist with the progress of the Inquiry, these reports have been subdivided into two categories.

3.3 First there are the two reports that summarise the results of the investigations and form a part of this evidence. These are Core Inquiry Documents and comprise *The Geology and Hydrogeology of the Sellafield Area: Interim Assessment: December 1993 ("Nirex Report 524")* [COR/517] published in 1993, and *Sellafield Geological and Hydrogeological Investigations: Factual Report - Compilation of Maps and Drawings ("Nirex Report SA/95/002")* [COR/518]. This latter report presents the data that have arisen from the investigations and, in response to the Secretary of State's statement under Rule 6(10) of the Town and Country Planning (Inquiries Procedure) Rules 1992, addresses his wish to be informed about the results available so far from studies and surveys of the geology and hydrogeology of the site. The report also lists the detailed factual and interpretation reports published by Nirex. I refer to over 35 key drawings in my evidence; the other drawings lie there for information. A copy of *Nirex Report SA/95/002* [COR/518] was sent to Cumbria County Council on 6 July 1995. It comprises 180 drawings as follows:

i. location maps showing where the investigations have been carried out;

ii. maps and sections showing the geological and geophysical characteristics of the area investigated;

iii. hydrogeological investigation drawings showing the results of testing carried out in boreholes and of regional surveys of the near-surface hydrogeology;

iv. maps showing the distribution of earthquakes that have occurred around Sellafield;

v. results of the groundwater pressure monitoring carried out in the deep boreholes;

vi. compiled summary drawings of the data collected during the drilling of each of the deep boreholes;

vii. compiled summary drawings showing the rock properties measured in the laboratory on core samples from the deep boreholes, together with rock properties interpreted from geophysical logs; and

viii. compiled summary drawings of the results of the chemical analyses carried out on samples of groundwater obtained from the deep boreholes.

3.4 Second are Nirex Reports which are referenced to provide details of where the detailed data can be found if anyone should wish to consult it. They comprise mainly factual reports which have not been published, but are available at the Nirex offices in Cumbria for reference on request to Nirex. It is only because of the number of the factual reports (around 1600 volumes) that they have not been made widely available. This second category of documents is referenced with curved brackets, for example {107} and {S/95/008}, the number referring to the Nirex Report Number. The data contained in these reports is summarised in the documents included in the first category identified in Paragraph 3.3.

Structure of Evidence

3.5 Section 4 of my evidence describes the investigations carried out so far at Sellafield into the geology and hydrogeology of the site. Reference is made to two appendices which provide more detail on the scope of the investigations and on the establishment of baseline hydrogeological conditions.

3.6 Section 5 provides a general introduction to the geology of the Sellafield site and establishes the framework within which I will then describe the main conclusions which arise from the investigations.

3.7 Sections 6 to 8 summarise our understanding of the characteristics of the site in relation to the three key areas of uncertainty to be addressed by the RCF:

i. groundwater flow and radionuclide transport (Section 6);

ii. natural and induced changes to the geological barrier (Section 7); and

iii. design and construction of the repository (Section 8).

3.8 In each of sections 6 to 8 the current understanding is described and explained and the remaining uncertainties which need to be resolved, are identified. An explanation is given of which of these can and are being addressed by further surface-based investigations. Finally those issues are identified which, because of the inherent limitations of surface-based investigation techniques, can only be addressed in the RCF.

3.9 In Section 9, I present my conclusions. The significant geological and hydrogeological characteristics interpreted from the results so far of the investigations are summarised. The remaining uncertainties that need to be

addressed and that can only be addressed by investigations in the RCF are highlighted.

Definitions

3.10 One of the main threads which extends through my evidence is the concept of 'flow zones'. Using Full Sector Tests (Table A.7, Appendix 1) in boreholes, zones in the rock are identified through which water can be induced to flow. These zones are called 'flow zones'. Using data from the boreholes and from analysis of the rock cores, these flow zones are characterised. In some cases the flow is found to occur along one or more fractures in the rock. These fractures are termed 'flowing fractures'. In other cases, particularly in the Brockram and sandstones, flow cannot be assigned to particular fractures since it may, for example, be occurring partially or completely through the rock matrix. In these cases the flow zone is referred to as a 'flowing feature' {S/95/006}.

3.11 The individual flowing fractures combine together to form 'networks of connected fractures' through which groundwater flow occurs. Although we can observe and characterise individual flowing fractures, we need to develop conceptual models to describe the networks of connected fractures because we cannot directly observe or characterise them using boreholes drilled from the surface. We can, however, infer certain characteristics of the networks from observations made in the boreholes. These matters are described in Section 6 of my evidence.

3.12 The Sellafield site (the 'site') refers to the area that has been investigated. The site has been subdivided into four areas within which different studies have been carried out (Paragraphs 4.2 - 4.6).

3.13 As far as possible, technical terms used in my evidence are explained as they arise. However, recognising the breadth of my evidence, it is inevitable that terms may be used which are unfamiliar to the reader. A full glossary of technical terms has been compiled to which reference should be made for the definition of all such technical terms (*Glossary of scientific terms* [COR/519]).

4. INVESTIGATIONS SO FAR

4.1 Nirex has adopted a systematic approach to the design and implementation of its investigations of the site. The process of investigating the geology and hydrogeology of the area is given the name of 'site characterisation'. A wide range of technical specialists and techniques has been used in the conduct of the work. Care has been taken to avoid undue reliance on any single technique in the investigation and interpretation of the ground conditions.

Geographical Location of Investigations

4.2 The studies carried out in West Cumbria have been contained primarily within four areas designated as the 'Region', 'District', and 'Site' areas (Figures 4.1 and 4.2) and the Potential Repository Zone ('PRZ') area (Figure 4.3).

4.3 The Region is an area onshore and offshore of approximately 60 km by 65 km

for which information has been gathered on geological features which might have relevance to a repository safety assessment. Existing published sources of information and commercial offshore seismic survey data have been used. Additional data, including structural geological data relevant to seismicity studies and geological data to place the Sellafield site into its broader geological framework, have been collected from wider areas extending for distances of over 100 km from Sellafield.

4.4 The District is an area of approximately 20 km by 30 km within which geological features may have direct relevance to a repository. Within this area Nirex has commissioned new geological, geophysical and hydrogeological investigations. These investigations have been supplemented by study of data from past mining activities and other sources of information.

4.5 The Site area immediately around the PRZ covers approximately 5000 hectares. All the Nirex Deep Boreholes ('Boreholes') are located in this area (Figure 4.2).

4.6 Since 1992 the characterisation activities have increasingly concentrated on the PRZ, leading to a greater level of detailed understanding of this particular area (Figure 4.3).

Scope of the Investigations

4.7 The extensive programme of surface-based investigations carried out so far comprises:

i. geophysical surveys carried out onshore, offshore, from the air and within boreholes;

ii. regional surveys comprising hydrogeological surveys, geological mapping and characterisation of the Quaternary deposits;

iii. boreholes at twenty two locations with a total of 25,712 metres of drilling. The deepest borehole is 1,950 metres deep. Most of the drilling has been carried out to obtain continuous core of the rock penetrated;

iv. the rock cores have been photographed, geologically logged and samples selected for routine and specialist characterisation in the laboratory;

v. hydrogeological testing has been carried out in the boreholes to determine groundwater pressures, rock hydraulic conductivity and other parameters which define how groundwater will move through the rocks;

vi. samples of groundwater have been obtained from the boreholes, analysed and the results corrected for the effects of drill fluid contamination with the aid of chemical tracers added to the drill fluids;

vii. instrumentation has been installed in twenty two boreholes for long-term monitoring of groundwater pressures;

viii. monitoring of earthquakes and acoustic emissions has been carried out;

ix. fractures in the rocks have been characterised both at the surface and in boreholes;

x. geotechnical studies have been undertaken to determine the mechanical behaviour of the rocks; and

xi. the results of the investigations have been interpreted. This has included

the development of a range of numerical models.

4.8 Appendix 1 describes the scope of these investigations and the sources of information on the results.

Baseline Hydrogeological Conditions

4.9 Carrying out investigation and construction activities at the site perturbs the groundwater pressures and can perturb the geochemical characteristics of the groundwater. The perturbations caused by construction of the RCF are likely to be more extensive than those caused so far by surface-based investigations. It is therefore important to have established both the groundwater pressures and the geochemical conditions with an adequate level of confidence before construction of the RCF commences. This is the concept of being able to define the 'baseline hydrogeological conditions'. Appendix 2 reviews the information obtained from the investigations so far and shows that baseline conditions have been established in terms of groundwater heads and geochemical conditions.

5. GEOLOGICAL STRUCTURE

Introduction

5.1 This section of my evidence provides a general introduction to the geological structure of the Sellafield site which will form the framework within which I will then describe the main conclusions from the investigations.

5.2 Reference is made to two reports (*Nirex Report 524* [COR/517] *and Nirex Report SA/95/002* [COR/518]) which together provide a more detailed description of the geology of the area for those who wish to obtain a more detailed and comprehensive description.

Geological Structure of the Site

5.3 The Borrowdale Volcanic Group of rocks ('BVG'), the potential repository host rock, crops out (is at the surface) in the north-east of the Site area (see Drawing No. 10032 in *Nirex Report SA/95/002* [COR/518]). Towards the west, the BVG is overlain by a sequence of cover rocks. These comprise Triassic sandstones (Ormskirk Sandstone, Calder Sandstone and St. Bees Sandstone) and a group of Permian rocks designated the 'Cumbrian Coast Group' (See Drawing No. 10059 in *Nirex Report SA/95/002* [COR/518]). Figure 5.1 is a geological sequence in the Sellafield Region area and Figure 5.2 is a geological cross-section to illustrate the geological sequence and structure of the PRZ.

5.4 To the west of the Fleming Hall Fault Zone, Carboniferous rocks, dominantly comprising limestones, occur between the Cumbrian Coast Group and the BVG (Figure 5.2). Within the PRZ the top of the BVG is between approximately 400 metres and 600 metres below ground surface. At the coast the top of the BVG is some 1500 to 1600 metres below ground level and by 10 km offshore the surface has fallen to 3000 metres below sea level. (Contours on this top basement surface are shown in Drawing Nos. 10051 to 10054 in

Nirex Report SA/95/002 [COR/518]).

5.5 This top basement surface is also shown as a three-dimensional visualisation in Figure 5.3. This diagram is a view from the south-west of the District area and shows the shape of the top surface of the BVG. The way in which the surface drops in elevation towards the west can be seen as can the sharp changes in the slope associated with fault displacements. In the onshore area these faults generally trend in a north-west to south-east direction. Other fault directions do occur, the most notable of which are the east-north-east to west-south-west trend shown by the faults within the Seascale Fault Zone.

Geological Structure of the PRZ

5.6 The investigations of the geology and hydrogeology of the site have progressively been focused on the PRZ and on the proposed position for the RCF.

5.7 The general structure of the PRZ is illustrated in Figure 5.4. This is a view from the south-east (with the overlying sandstones removed) showing the Brockram (part of the Cumbrian Coast Group) overlying the BVG. The main faults that have been recognised from the seismic surveys are also shown.

5.8 To the west (left hand side of Figure 5.4) of the RCF the Fleming Hall Fault is shown and to the west of this, the Carboniferous Limestone (shown in blue) occurs between the Brockram and the BVG. In this area the eastern limit of the Carboniferous strata is marked by the Fleming Hall Fault. Further to the north this eastern limit trends in a north-easterly direction away from the fault (See Drawing No. 10054 in *Nirex Report SA/95/002* [COR/518]).

5.9 Three reports on the results of investigations in this area have been published by Nirex in 1995 dealing with the geological structure of the PRZ, the flow zone characterisation of the RCF area, and the geology and hydrogeology of the RCF South Shaft location {Nirex Report Nos. S/95/005 to 007}. This sub-section of my evidence summarises the main conclusions of these reports.

5.10 The progress reported in *Nirex Report 525, Scientific Update 1993, December 1993 ("Nirex Report 525")* related to the subdivision of the BVG has been continued. *Nirex Report 525* (paragraph 3.3, page 16) [COR/505] stated:

"Prior to the commencement of the Nirex studies, BVG in the local area was classified as a thick sequence of undifferentiated volcanic tuffs (consolidated volcanic ash) and lava flows. One of the major achievements of work reported here has been to establish a subdivision of the rocks into several formations which can be correlated between boreholes over distances of several kilometres. This subdivision has enabled the structure of the BVG to be defined in more detail. It is also becoming apparent that the hydrogeological properties of the rocks are related to this same stratigraphic subdivision. "

5.11 An interpretation of the geological structure of the proposed RCF South Shaft area is shown in Figure 5.5. This shows the two formations recognised in this part of the BVG: the Fleming Hall Formation and the Brown Bank Formation. The Fleming Hall Formation has been further subdivided into three members: the Longlands Farm Member, the Sides Farm Member and the Town End Farm Member.

5.12 A general relationship has been observed between rock quality (inferred from geophysical logs and measurements on the cores) and the identified members and formations. An alteration zone in the Longlands Farm Member, the Sides Farm Member (both in the Fleming Hall Formation) and the Brown Bank Formation have been shown to be intervals characterised by lower rock strength and higher fracture frequency relative to the other parts of the sequence in the RCF South Shaft area. The distribution of these rock units is shown in Figure 5.5.

5.13 The analysis of the fractures seen in the cores of BVG obtained from the Boreholes is indicating that the orientation characteristics of the fractures vary markedly with depth. Structural domains have been defined in which the fractures have similar characteristics {S/95/007}. The boundaries between these domains, in the majority of cases, are either lithological boundaries or faults.

5.14 Some progress has been made in extrapolating the detailed geological structure established in the RCF South Shaft area out into the PRZ. The geological cross-sections and serial section at the 650 metres below Ordnance Datum ('bOD') level (Drawing Nos., 10061, 10062 and 10067 in *Nirex Report SA/95/002* [COR/518]) demonstrate the progress being made in the extrapolation. The results of the 3-D seismic reflection trial survey will further assist in extending this extrapolation across the wider PRZ area.

6. GROUNDWATER FLOW AND RADIONUCLIDE TRANSPORT

INTRODUCTION

6.1 The main way in which radionuclides can be transported away from a repository is by flow of groundwater. The groundwater flow through the rocks is thus an important factor in determining the performance of a repository in terms of its ability to limit releases of radioactivity.

6.2 The Nirex repository concept requires that the geological barrier must perform two key functions. Firstly it must ensure that there are low flows of groundwater through the repository so that the physical and chemical barriers can operate to retain short-lived and most long-lived radioactivity. Secondly, the geological barrier must ensure that there is sufficient dilution of those residual radionuclides released from the vaults in order to limit concentrations in groundwater reaching the surface.

6.3 This section of my evidence examines the information and understanding of groundwater flow at the site that has emerged from the investigations carried out so far. It presents the information that shows the groundwater flows through the BVG are low. It then presents the information to indicate that the groundwater system provides dilution of any water leaving a repository located in the BVG. Finally, conclusions are drawn concerning the extent of our current understanding of the groundwater system and the remaining uncertainties which need to be addressed in the RCF.

6.4 The judgments that currently need to be made about aspects of the groundwater flow system, because of inherent limitations with surface-based investigations, are identified.

6.5 The evidence in this section is presented under the following headings:

Groundwater flows This is addressed by consideration of:

- influence of fractures on groundwater flow;
- characterisation of flow zones;
- fracture connectivity;
- groundwater heads and gradients; and
- geochemistry.

Dilution The current understanding regarding the extent to which the groundwater system provides dilution of groundwater which may leave a repository is reviewed; and

Remaining uncertainties The current understanding of the groundwater system is reviewed and the remaining geological and hydrogeological uncertainties affecting understanding of groundwater flow are summarised. Conclusions are drawn as to which of these remaining uncertainties can be addressed by further investigations from the surface and which need to be addressed in the RCF.

I. GROUNDWATER FLOWS

6.6 Old hard rocks, such as the BVG, contain natural fractures that have developed in response to the long history of formation, burial and the tectonic processes to which they have been subjected. The rock between the fractures has a very low hydraulic conductivity (i.e. a low ability to permit water to flow through it) and water will tend, therefore, to flow through fractures. In order for the fractures themselves to be able to transmit water for any distance through the rock they must be both open and connected together. Thus, the existence of fractures in the rock is not, in itself, evidence that the rock mass (intact rock plus fractures) is able to transmit water. Not all fractures are identical and some are better able to transmit water than others: such fractures are the flowing fractures.

6.7 That the BVG contains fractures can easily be seen from a cursory examination of the rocks exposed at the surface and from examination of the cores from the boreholes. The first aspect of the consideration of groundwater flow through the BVG is thus to establish the extent to which fractures have a dominant influence on controlling groundwater flow through the rocks. The second is to identify which of these fractures are important as possible pathways for groundwater flow.

Influence of Fractures on Groundwater Flow

6.8 In order to establish the extent to which the fractures in the rock have an important influence on the ability of the BVG to transmit water, tests are carried out on blocks of rock with and without fractures and the hydraulic conductivity of the two sets of results compared. If the fractures are dominating

the ability of the rock to transmit water we should expect to see that the tests on samples containing fractures yield higher values of hydraulic conductivity than corresponding tests on samples without fractures. The simplest way of doing this is to test small core samples of rock in the laboratory (because these can be seen not to contain fractures) and then to carry out tests over lengths of many metres in boreholes having first demonstrated from an examination of the borehole cores that such test lengths contain fractures.

6.9 The way in which this was done is shown in *Nirex Report 525*, (Figure 10, page 17) [COR/505] which shows the values of hydraulic conductivity measured in 50 metre long sections in the Boreholes and on small core samples in the laboratory. The results for the BVG are summarised in Figure 6.1(a). The field values (shown in green) can be seen to have hydraulic conductivity values about 2 orders of magnitude greater than the values (shown in red) obtained on small core samples in the laboratory. The difference between these two sets of data thus indicates the importance of fractures in determining the overall hydraulic conductivity of the BVG.

6.10 Having established that the hydraulic conductivity of the BVG is controlled by fractures, the next aspect of the investigations was to determine whether all the fractures behave in a similar manner or whether there is a sub-set of fractures which have the dominant influence on controlling groundwater flow.

6.11 Full Sector Tests (as described in Table A.7, Appendix 1) are carried out in the Boreholes to identify those sections of the borehole wall through which groundwater can be induced to flow. This was reported in *Nirex Report 525* [COR/505] (page 19) which described the observation that groundwater flow in the BVG, and, to some extent in other formations, occurred through a small subset of fractures. It was thus shown that the dominant influence on groundwater flow through the BVG was not the complete set of fractures but rather this small subset of fractures. The zones in the boreholes through which groundwater flow can be induced are called 'flow zones'. Using data from the boreholes and from analysis of the rock cores, these flow zones have been characterised. In some cases the flow is found to occur along one or more fractures in the rock. These fractures are termed 'flowing fractures'. In other cases, particularly in the Brockram and sandstones, flow cannot be assigned to particular fractures since it may, for example, be occurring partially or completely through the rock matrix. In these cases the flow zone is referred to as a 'flowing feature' {S/95/006}.

6.12 The importance of these flow zones in controlling the hydraulic conductivity of the BVG can be seen from the analysis of the borehole tests described in Paragraph 6.9 above. This was done by comparing the hydraulic conductivity values in those sections of the boreholes which had been shown to contain flow zones with those from sections without identified flow zones. Figure 6.1 (b) shows these results. For those sections containing flow zones (shown in green) the median value was between 10^{-8} and 10^{-9} metres/second and, for those sections without the flow zones (shown in red), the median value was between 10^{-10} and 10^{-11} metres/second. The difference in the median values of over two orders of magnitude of hydraulic conductivity clearly shows the marked influence of the presence of flow zones on groundwater flow in the BVG.

6.13 It is relevant to note that the measured values of hydraulic conductivity reported above are similar to those predicted in 1989 in *PERA* (Table 8.2)

[COR/501]). Thus, the results obtained from the testing were generally as expected.

6.14 The testing described above demonstrated the importance of the flow zones and showed that the hydraulic conductivity values in the BVG in sections of boreholes without such zones were lower than those obtained from sections with such features. An outstanding issue was, however, to determine what, if any, influence the other fractures in the BVG (i.e. not flowing fractures) had on the hydraulic conductivity of the BVG as a whole. This was examined by investigations carried out during 1994 to measure the hydraulic conductivity of the rock mass remote from (as well as close to and across) the identified flowing fractures. This was the Short Interval Hydraulic Testing (see Table A.8 in Appendix 1). By making measurements over short lengths of borehole (1 to 2 metres long) flow zones are measured separately and the hydraulic conductivity of the rock mass containing the other fractures can be determined. The results of this testing, which took place in the BVG in Borehole RCF3, are shown in Figure 6.2. The flow zones (shown as blue arrows) were identified from Full Sector Tests carried out prior to the Short Interval Hydraulic Testing. The Short Interval Hydraulic Testing indicated the presence of two main clusters (labelled 1 and 2) and a third smaller cluster (labelled 3) of higher values, but still with hydraulic conductivity values of less than 1×10^{-8} metres/second. Unsurprisingly, these clusters appear to be associated with the previously identified flow zones. More importantly, higher values from the Short Interval Hydraulic Testing are not found between the identified flow zones. In these sections of the borehole, the tests gave hydraulic conductivity values of less than 1×10^{-11} metres/second. The distribution of these values appears very similar to the values obtained from the laboratory tests on core samples of unfractured BVG. This shows that the background fractures have little influence on the overall hydraulic conductivity of the BVG.

6.15 The testing has thus indicated some important features of the BVG:

i. the hydraulic conductivity of the BVG is controlled largely by the presence of fractures in the rock;

ii. the rock without fractures has a very low hydraulic conductivity as shown by the tests on core samples in the laboratory;

iii. flow zones have been identified in the boreholes and shown to have a significant influence on the hydraulic conductivity of the BVG; and

iv. the fractures in the BVG, other than the identified flowing fractures, have little influence on the hydraulic conductivity of the BVG as shown by the Short Interval Hydraulic Testing which gave values for the background, fractured BVG very similar to the laboratory tests on unfractured BVG.

6.16 The results of the hydrogeological testing described above have indicated that the BVG has a low hydraulic conductivity. However, because of the influence of the flowing fractures in controlling groundwater flow and the importance of taking due regard of the ways in which these hydrogeologically significant features form networks of connected fractures, it is not justifiable to take measurements of hydraulic conductivity from small scale tests in the laboratory or in the boreholes and to apply these directly to groundwater flow models which represent the large scale system. The process of deriving large scale hydrogeological parameters (effective parameters) from the testing for use in

the modelling is described in *Nirex 95* [COR/522].

Characterisation of Flow Zones

6.17 Having shown the importance of the flow zones in controlling the hydraulic conductivity of the BVG, the next important issue is to characterise them so that they can be appropriately incorporated into groundwater flow models of the site. This aspect of flow zone characterisation is considered in this sub-section of the evidence.

6.18 In 1993 when *Nirex Report 525* [COR/505] was published, there was little information on the origin or nature of these flow zones, other than that they could be identified, by testing, where they intersected a borehole. The Royal Society Study Group shared the Nirex view that characterisation of the flow zones was important as the basis for defining the organisation of groundwater pathways within the BVG. They stated in their report *(The Royal Society, Disposal of Radioactive Wastes in Deep Repositories, November 1994 ("The Royal Society, November 1994")* [COR/605] (Section 6.8, page 110):

"However, an important unresolved issue has been encountered: the most detailed geological and hydrogeological data yet available have failed to yield a simple relationship between the inferred pattern of fracturing in the repository host rock, the Borrowdale Volcanics, and the organisation of groundwater pathways."

6.19 The studies so far undertaken by Nirex have characterised the flow zones in nine boreholes within the PRZ, namely Boreholes 2, 4, 5, RCF1, RCF2, RCF3, RCM1, RCM2 and RCM3 {S/95/006}.

6.20 Analysis of the flow zones in the RCF area (defined as the area of Boreholes RCF3, RCM1 and RCM2) has indicated an association between the occurrence of flow zones and the geological succession of the BVG. An interval in the Longlands Farm Member between 580 metres and 630 metres bOD was identified as containing flow zones in all three boreholes. The top of the Longlands Farm Member from the base of the Brockram to 500 metres bOD and the Sides Farm Member at 670 metres bOD also showed some tendency to contain flow zones. The Town End Farm Member is notable in the RCF South Shaft area as being largely unfaulted, comprising high quality rock and being almost devoid of identified flow zones.

6.21 Characterisation of the flow zones in the RCF South Shaft area has also indicated an apparent linear decrease in flow zone hydraulic conductivity with depth {S/95/006}.

6.22 In total, only 154 flow zones have been identified in the boreholes which together amounted to over 8,000 metres of drilling. This is about 0.5% of the total number of fractures encountered in the boreholes. Fifty percent of the flow zones occur in the sandstone, 8% in the Brockram and the remaining 42% in the BVG. Thus, only 64 flow zones have been identified in the BVG in the area studied.

6.23 The analysis of these flow zones {S/95/006} has been carried out to identify specific features responsible for the inflow of water and to investigate the mineralogical and petrological character of these and adjacent features seen in

the borehole cores. In particular, the mineralisation, distribution, orientation and character of the features have been examined.

6.24 The minerals and fluid inclusions which occur in the fractures provide information which can be used to interpret the time when the fractures were created and their history in terms of further periods of movement which may have occurred since their formation. Stable isotope signatures and fluid inclusion characteristics of the fracture minerals provide an insight into the chemistry of the mineralising fluids and the conditions under which mineralisation occurred {520} {SA/95/001}. The investigations of fracture mineralisation commenced with a general review of the history of mineralisation and the establishment of a series of mineralisation episodes which have affected the rocks at different times in their history and have resulted in the deposition of different minerals within the fractures. This work was reported in 1993 {520}. Subsequently, the studies of fracture mineralisation have concentrated on the intervals containing flow zones {S/95/006}.

6.25 These studies have enabled the establishment of a well-defined history of fracture movement and discrete mineralisation events affecting the site. Nine broad but discrete mineralisation episodes (designated ME1 to ME9) have been recognised. These can be correlated with regional patterns of mineralisation and diagenesis, both in the East Irish Sea Basin and in the Lake District. Limited potassium-argon dating of illite clay mineralisation in fault gouge, and correlations with regional patterns of mineralisation have enabled the periods of fracture development and mineralisation to be dated.

6.26 The mineralisation episodes are summarised in Table 6.1. In most cases there appears to be no particular relationship between fracture orientation, fracture type and mineralisation episode. Each mineralisation episode, with the exception of ME2, has reactivated and reutilised the pre-existing fractures and veins of earlier episodes. This is because the carbonate- or hematite-dominated fracture-fill is relatively weakly bonded to adjacent wallrock and therefore the veins represent planes of weakness, which are readily reactivated in preference to the formation of new fractures.

6.27 The following conclusions have been reached from these studies of the flow zones {S/95/006}:

i. flow zones are not associated with a single, consistent geological characteristic in the boreholes studied;

ii. the flow zones in the Sherwood Sandstone Group are largely matrix flow with some contribution from fractures. For those flow zones associated with fractures, there is a tendency towards shallow south-west dipping orientations, which reflects the dip of the bedding in the rocks;

iii. in the Brockram the flow zones are associated with either matrix flow or fracture flow;

iv. in the BVG the flow zones are mostly associated with mineralised flowing fractures. When flow in the BVG can be associated with specific flowing fractures, there is a slight tendency for these to be oriented north-east dipping;

v. there is a broad relationship between flow zones and the occurrence of ME6 carbonate mineralisation. Of the 78 flowing fractures identified and

examined so far, more than 80% were associated with carbonate/hematite mineralisation (Figure 6.3). Seventy two have been assigned to a particular mineralisation episode and, of these, 48 (67%) were assigned to mineralisation episode ME6 (Figure 6.4);

vi. there is no obvious relationship between flow zones and faulting in the St. Bees Sandstone. Within the BVG, 20% of the flow zones occur within fault rock and 47% within 5 metres of a fault. The association between ME6 mineralisation and faulting is variable between individual boreholes;

vii. there is a strong relationship between flow zones and the presence of ME9 late calcite mineralisation. ME9 post-dates all observed fault structures observed in borehole cores. The type of late calcite crystals found appears to be related to the current salinity of the groundwater. If the late calcite can be successfully dated, it may help to indicate the period of time for which the present salinity profile has existed;

viii. the close association between flow zones, proximity to faults, ME6 mineralisation and north-east dipping fractures suggests the possibility that groundwater flow in the BVG is related more to the larger scale distribution of ME6 mineralisation in the rock mass, rather than the type, orientation or intensity of individual flowing features or fractures; and

ix. there is an apparent linear reduction in measured hydraulic conductivity values in the flowing fractures with depth.

6.28 Relating these various conclusions to the understanding of the geological history of the site suggests that the majority of the flowing fractures probably owe their origin to fracture movements which occurred around the early to middle Triassic, some 200 million years ago when the ME6 mineralisation episode occurred. These fractures probably remained as flowing features during subsequent periods of fault movement and mineralisation. The last significant period of fault movement occurred around 100 million years ago as indicated by the dating of clays in fault gouges. The flowing fractures appear to have remained hydraulically active subsequently as indicated by the development of ME9 late calcite. Such mineral precipitation, and associated dissolution, is likely to have altered the specific characteristics of individual fractures and may have caused some adjustments to the networks of connected fractures over time. However, the evidence so far supports the view that the ME6 fracture network has provided the framework for the network of connected fractures and that this framework has persisted for some 200 million years.

6.29 Although the understanding of these important flowing fractures has developed significantly over the last eighteen months, the understanding concerning the physical character of these fractures is based solely on observations and measurements made on small diameter core samples. As noted in Paragraph 6.27 viii. above the groundwater flow in the BVG may be related more to the larger scale distribution of ME6 mineralisation in the rock mass rather than the type, orientation or intensity of individual flowing fractures. It is therefore necessary to examine the larger scale features using techniques other than observations and measurements on small diameter core samples. This has been done in the Boreholes by examining results from hydraulic testing to provide indications of the ways in which the flow zones

may form networks of connected fractures over longer length scales. This issue of 'connectivity' is addressed in the next sub-section.

Fracture Connectivity

6.30 Showing that the flowing fractures have an important influence on the hydraulic conductivity of the BVG is only the first step in determining groundwater flows within and through the BVG. The second, and perhaps more important, step is to determine the way in which these flowing fractures are connected. If these fractures are well connected within the BVG and also connected on through the overlying rock formations, there could be higher flows through a repository and lower subsequent dilution than if the flowing fractures are poorly connected both within the BVG and to the overlying formations. These issues are addressed in this sub-section of the evidence.

6.31 From analysis of the Environmental Pressure Measurements in the Boreholes (Table A.7, Appendix 1) it was suggested by Nirex that the flowing fractures were hydrogeologically linked, possibly over hundreds of metres (*Nirex Report 525*, paragraph 4, page 22 [COR/505]). However, at that time (in late 1993 and early 1994) when the groundwater flow models which subsequently formed the basis for the safety assessment studies reported in *Nirex 95* [COR/522] were being developed, there was no direct information on the form of these connections. Judgments were made concerning the manner in which the flowing fractures were connected to form the extended networks through which flow predominantly occurs.

6.32 These judgments were used to inform the development of a hydrogeological conceptual model. In this model, the main flow channels in the rocks were described as networks of connected fractures having length scales ranging up to hundreds of metres. This description implied a relatively high vertical hydraulic conductivity for groundwater flow in the BVG and Basal St. Bees Sandstone compared with conductivity implied by the rock matrix and individual fractures.

6.33 The nature of the connections in the fracture systems has subsequently been investigated through Fracture Network Testing, Cross-Hole Hydraulic Testing and from the Borehole RCF3 Pump Test (see Table A.8 in Appendix 1 for further sources of information on the nature of these tests). Further information has been obtained from the Regional Hydrogeological Surveys.

6.34 Each of these programmes of testing represents 'State-of-the Art' scientific activities incorporating numerical modelling to assist with the design of the testing, precision monitoring of the test outputs and detailed analysis of the test results. The detailed interpretation of the testing has not yet been completed. Hence, the results presented in my evidence are preliminary, but are presented in as much detail as possible to illustrate the nature of the data being generated and the implications of these data.

Fracture Network Testing

6.35 The Fracture Network Testing was carried out in Borehole RCF3 and is described in Table A.8 in Appendix 1.

6.36 The results are summarised in Figure 6.5. The diagram shows the layout of the test sections in relation to the observed flow zones and identified faults. The locations of the test sections are shown together with an indication of where responses were observed in adjacent sections. The responses in the monitoring section are quantified as the drop in pressure in those sections as a percentage of the drop in pressure in the test section as a result of pumping. Many of the sections of the hole which were tested yielded such a small flow from the test section (shown as 'NF' on the diagram) that they did not produce any measurable response in the adjacent sections. The hydraulic conductivity values are shown as derived from the short-term Environmental Pressure Measurements.

6.37 Those sections of the borehole which did not generate responses in other sections or within which responses were not generated by testing in other sections are shown as Zone I. Those sections in which responses were generated by testing elsewhere but when tested themselves did not generate responses are grouped as Zone II. Those sections which generated responses elsewhere and which responded to testing elsewhere are grouped as Zone III and shaded yellow. The fact that Zone III bands are narrow suggests that there are not extensive connections along the length of the borehole. If there were extensive connections, widespread responses would have been observed. There is also seen to be a direct relationship between the Zone III sections and the presence of flow zones in the borehole as shown in Figure 6.5. Areas of higher response are also seen to correspond to the clusters of higher conductivity values obtained from the Short Interval Hydraulic Testing. These are shown in red in Figure 6.5 and are derived from Figure 6.1. This programme of testing thus demonstrates the direct influence of flow zones on the ability to pump water from the fracture system, and hence recognises the importance of these flow zones as potential pathways for groundwater flow. It also demonstrates the limited extent of connections in the fracture system along the length of the borehole. By its nature, this programme of Fracture Network Testing cannot identify connections within the fracture system in lateral directions away from the borehole.

Cross-Hole Hydraulic Testing in Boreholes 2 and 4

6.38 Cross-Hole Hydraulic Testing has been carried out between Boreholes 2 and 4 (Table A.8 in Appendix 1). The objective of this testing was to characterise the flow zones within Borehole 2 and to establish the connectivity of these both within the borehole (Borehole 2) and with a neighbouring borehole (Borehole 4). The programme of testing comprised seven periods of pumping from individual sections of Borehole 2, each of which contained identified flow zones, whilst monitoring zones above and below the pumped section (as for the Fracture Network Testing) and whilst monitoring zones in the adjacent Borehole 4 using the installed groundwater monitoring string. Boreholes 2 and 4 are approximately 120 metres apart. The rock between Boreholes 2 and 4 had previously been structurally characterised by cross-hole seismic tomography. Borehole 2 is approximately down-dip of Borehole 4.

6.39 The Cross-Hole Hydraulic Testing thus provided the opportunity to examine the way in which flowing fractures might be connected on a larger scale than

was possible using the Fracture Network Testing. It also provided the opportunity to examine the possible coincidence of the flow zones with known geological structures. Unlike the Fracture Network Testing, the test sections for the Cross-Hole Hydraulic Testing were only located in parts of the borehole which contained identified flow zones. Hence, some responses were observed in all tests.

6.40 A summary of the results obtained from the testing is shown in Figure 6.6. This figure shows the locations of five of the seven pumping sections. (More detailed results, including the data from the other two pumping sections omitted from Figure 6.6 for clarity, are shown as Drawing No. 10090 in *Nirex Report SA/95/002* [COR/518]). The figure also shows the responses observed in Borehole 2 to the pumping of sections in Borehole 2. It confirms the pattern of responses seen in similar tests carried out in Borehole RCF3 and shown in Figure 6.5. The figure also shows the responses observed in Borehole 4 to the pumping in Borehole 2. The geological structure between the boreholes is derived from the results of the seismic tomography survey and the position of main faults (Fault 1 and Fault 200) is shown. The diagram shows that responses from each pumping test in Borehole 2 were only seen in limited parts of Borehole 4 and that these responses did not occur along the lines of the major faults known to extend between the two boreholes. This suggests that the flowing features, at least in this area, are not synonymous with these larger faults. It is also noted that the observed responses from each test are confined to a limited vertical sequence of BVG. None of these tests show responses which are observed through the full sequence of the BVG. It should be noted that the responses observed in Borehole 4 were extremely small. Many were close to the limits of resolution of the monitoring equipment and of a similar magnitude to the natural, short-term cyclic fluctuations observed in the monitoring network dataset (See Paragraphs B.2.14 - B.2.15 in Appendix 2).

Borehole RCF3 Pump Test

6.41 The Borehole RCF3 Pump Test is a programme of tests carried out by pumping from sections of Borehole RCF3 covering each of the three main geological units: the St. Bees Sandstone, the Brockram and the BVG. The responses of the groundwater system to the pumping are being monitored in the groundwater pressure monitoring system (see Table A.11 in Appendix 1). At the time of preparing this evidence the testing was still in progress and the results had not been interpreted in detail. However, preliminary results are presented to illustrate the nature and implications of the data being generated.

6.42 Some of the results of the Borehole RCF3 Pump Test are shown in Figure 6.7. (This drawing is a reproduction of part of Drawing No. 10092 in*Nirex Report SA/95/002* [COR/518] to which reference should be made for details of the locations of the various pumping sections and gauges installed in the borehole). It shows the groundwater pressures measured at eleven locations (15 gauges) in Borehole RCF3 during the pump test. The pressures (shown as calculated environmental heads) in those sections of the borehole being pumped are shown, together with the pressures measured in other sections of the borehole. (Responses measured in the other boreholes in the monitoring

network are shown in Drawing Nos. 10111 to 10131 in *Nirex Report SA/95/002* [COR/518].)

6.43 The heads in the various sections of the borehole have baseline values of around 80 metres above Ordnance Datum ('aOD'). During the Brockram test (Jan-Feb 1995) the pumping was carried out in the section containing gauges P9 and P10 (green lines in Figure 6.7). In Borehole RCF3 pressure changes can be seen in both these gauges but not in any of the other gauges. Similarly, in the sandstone test (March 1995) gauges P11 and P13 show the reduction in pressure in the pumped test section (red and mid blue lines). However, the other sections, including the recovering Brockram Zone, show no response to this pumping. On Figure 6.7 the BVG test is still in the drawdown stage. The responses in the pumped sections (P3 and P4) look slightly different from the responses in the pumped sections during the other two tests. This is because the head in the BVG is being kept constant for the duration of the test, rather than the flow rate from the test section being kept constant as with the other tests. (The pumped section for the BVG test is at approximately 640 to 680 metres bOD. It coincides with Cluster 2 in Figure 6.2 and with the lowermost Zone III section in Figure 6.5.)

6.44 During the BVG tests small responses have been observed in two sections immediately above (P5 and P6) the pumped section. No other responses were observed in Borehole RCF3. A similar pattern of responses is observed in other boreholes in the monitoring network (See Drawing Nos. 10111 - 10131 in*Nirex Report SA/95/002* [COR/518]).

6.45 A provisional conclusion from the Borehole RCF3 Pump Test is that there appears to be little connection between the BVG and the overlying sandstones.

Observations from Regional Hydrogeological Studies

6.46 The groundwater at depth in the BVG is saline and warmer than the near surface freshwater. The temperature differential arises from the natural geothermal gradient. Hence, the presence of deeper groundwaters at the surface, which could indicate the existence of connected pathways from depth through which flow was occurring, would be indicated by the presence of saline and/or warm waters at the surface. (This same principle is used in the Full Sector Tests to identify flow zones in Boreholes.) This issue has been examined by consideration of the variations in near-surface groundwater chemistry and temperature. (See Drawing Nos. 10097 - 10102 and 10206 - 10209 in *Nirex Report SA/95/002* for the chemistry data [COR/518].)

6.47 There is no evidence from these regional hydrogeological studies for the existence of direct natural connections from depth to the surface through which deep groundwater is flowing.

Groundwater Heads and Gradients

6.48 At its simplest level, groundwater will only flow if there is a head gradient. (There are other processes, such as diffusion, which can produce slow movement of groundwater, but these processes are much less significant than pressure induced flow.) The measurement of the heads thus forms an

important part of the characterisation of the site.

6.49 The information on groundwater heads at the time *Nirex Report 525* [COR/505] was published was restricted to that derived from interpretation of short-term Environmental Pressure Measurements in which data from an 8 or 16 hour test was used to extrapolate the in situ pressure. Referring to this, *Nirex Report 524*, (Volume 3, Section 4.4.2, page 4-4) [COR/517] made the following statements:

"The value of in situ pressure is therefore an interpretation of a dataset, it is not strictly a measurement or observation.....During the pressure recovery period, high conductivity intervals recover to much closer to their in situ pressure than low conductivity intervals. The degree of extrapolation for high conductivity intervals is consequently much less. In addition, the shape of the pressure recovery plot in low conductivity sections may be affected by pressure and temperature disturbances caused by the drilling process."

6.50 It was also noted in *Nirex Report 525* (Section 3.4, page 17) [COR/505] that the deep groundwater was saline and that it was therefore necessary to calculate 'environmental heads' to determine the potential for vertical flow. This stated:

"The groundwater at depth within the BVG is saline.....Saline water is more dense than fresh water and so, in order to assess the possible driving force for a vertical component of flow, the measured groundwater pressure must be converted to 'environmental' heads which take account of the influence of varying density. "

6.51 The results from this monitoring network that is now established and operational have provided data recorded continuously over many months (Drawing Nos. 10111 to 10131 in *Nirex Report SA/95/002* [COR/518]). These measurements have thus allowed for the groundwater system to settle down and recover from the effects of drilling and testing (see Appendix 2, Section B.2).

6.52 The current understanding of the distribution of groundwater heads at the Site is described in the following paragraphs.

Vertical Head Profiles

6.53 In general, there is a good agreement between the pressures and heads derived by long-term monitoring and those from Environmental Pressure Measurements carried out during drilling. There is some evidence, derived from interpretation of the Environmental Pressure Measurements, particularly in Boreholes 2 and 4, for local small scale variations in heads attributable to borehole history and pumping activities. It is possible that many of the minor variations apparent in the data from the short-term hydrogeological testing could have similar causes. The data from the long-term monitoring provides a means of developing confidence that the recorded pressures and calculated heads are free from perturbations caused by drilling or testing (See Appendix 2).

6.54 The general features of the groundwater head profile in the RCF area of the

PRZ are illustrated in Figure 6.8. This figure is derived from the long-term monitoring data for six boreholes. It shows how the environmental head varies with depth in the boreholes. Three distinct zones with different characteristics can be identified and are labelled Zones 1, 2 and 3.

6.55 In Zone 1 an upward gradient of about 12 metres head change in 170 metres depth of borehole (i.e. about 7%) is found above about 170 metres bOD. This contrasts with Borehole 8 (not shown in Figure 6.8) in which a 5% downward gradient is apparent in the upper 150 metres of the St Bees Sandstone. This overall pattern suggests that the upper 150 to 200 metres of the Sherwood Sandstone Group is an active aquifer system receiving recharge in the higher ground (Borehole 8) and containing coastward and upward moving freshwater for much of the area where ground level is below about 100 metres aOD. This may locally give rise to artesian flow in areas of depressed topography (e.g. Holmrook 13 Borehole).

6.56 Figure 6.8 shows that from about 170 metres bOD to the base of the Permo-Triassic rocks, little or no vertical gradient is apparent. In the area covered by the Boreholes shown in Figure 6.8 this absence of vertical gradient continues down through the upper 400 metres or so of the BVG. In some other Boreholes, for example Boreholes 2, 4 and 5, the top of Zone 2 is somewhat deeper and appears to coincide with the top of the Brockram. This pattern suggests that, over much of the PRZ, there is little or no head gradient to drive vertical flow in the upper portion of the BVG and that in some areas, this pattern extends through the Brockram and up into the Sherwood Sandstone Group.

6.57 In Zone 3 Figure 6.8 shows that at depth within the BVG an increase in environmental head occurs. In Figure 6.8 the boundary between Zones 2 and 3 is shown at 800 metres bOD. The level of this boundary is not precisely defined but it appears to lie between about 750 metres bOD and 900 metres bOD in the area of these boreholes.

Regional Head Distributions

6.58 Freshwater heads calculated from the borehole monitoring data are used to indicate whether there is a gradient which might give rise to components of flow in the horizontal direction. The results indicate a consistent pattern of head gradients towards the coast.

6.59 The gradient, which is regionally between 2 and 4% and locally up to 7% (in the PRZ), appears to be topographically related and is consistent regardless of the stratigraphy. Over areas covered by data, there appears to be no potential for the landward ingress of groundwater at levels between 100 metres and 800 metres bOD. Beneath this depth, data are limited but suggest that near the coast there may be a gradient in the opposite direction, i.e. towards the land.

Geochemistry

6.60 The geochemical characteristics of the water provide information on how the groundwater system has evolved over time, including providing evidence of past groundwater flow directions and mixing processes which are occurring

within the system. The interpretation of groundwater flow and mixing processes that arise from the geochemical studies thus provide independent evidence that can be compared with the predictions of groundwater flow derived from consideration of the physical charateristics of hydraulic conductivity and head.

6.61 The scope of the geochemical studies in terms of the range of analyses carried out has been described in Paragraphs A.8.1 to A.8.4 and in Table A.9 in Appendix 1. The manner in which chemical tracers are used to correct for drill-fluid contamination has been described in Paragraphs A.4.4 to A.4.5 in Appendix 1 and the extent to which the baseline geochemistry has been established has been reviewed in Section B.3 of Appendix 2.

6.62 Nirex Report 525 identified three groundwater regimes (Shown in Figure 13 of *Nirex Report 525* [COR/505]). These were:

i. a shallow, fresh-water occurring throughout the area within the 'Coastal Plain Regime';

ii. a saline water with a high bromine to chlorine ratio (relative to the brines in iii. below) occurring at depth towards the east of the area, within the 'Hills and Basement Regime'; and

iii. a deep brine with a lower bromine to chlorine ratio occurring at depth in the west of the area, within the 'East Irish Sea Regime'.

6.63 A detailed update of the hydrochemistry (i.e. the geochemistry of the water) of Sellafield, was published by Nirex in July 1995 {S/95/008}. This report focused on interpreting the greatly increased amounts of data that have become available since Nirex published the last interpretation of the geochemistry in 1993 in *Nirex Report 524*, (Volume 3, Section 3) [COR/517].

6.64 The newly available data are broadly consistent with the overall interpretation presented in 1993 (*Nirex Report 524*, Volume 3, Section 3 [COR/517]) even though there is now some 2.5 times the volume of data available as compared to 1993. Thus, the interpretation has confirmed that there appear to be the three major groundwater regimes identifiable across the site, correlating with distinct components to the groundwater salinity.

6.65 However, the recent data have also indicated that the freshwater can be subdivided into two types distinguished on the basis of the stable oxygen isotope data {S/95/008}. This newly identified type occurs locally beneath the Coastal Plain Regime where the freshwater, on the basis of the measured stable oxygen and hydrogen isotopes, is different from the shallow freshwater. This is clearly shown by the additional data, ringed in yellow on the lower part of Figure B.3.2 (Appendix 2) derived from 1995 data, which was not present in the earlier 1993 data. It is believed that this deeper water was recharged under colder climate conditions than currently exists, possibly during the Pleistocene.

6.66 The recognition of this fourth component, and the way in which it has enabled all the groundwater compositions so far observed at the site to be attributed to mixing between the four identified components, represents a significant advance in the understanding of the geochemistry of the Site. This is because it provides confidence that the pattern of groundwater type distribution has been revealed and that there are no longer any observed compositions that cannot be explained in terms of well defined mixing relationships.

6.67 The saline transition zone, which marks the interface between the fresh water above and the saline water below, is relatively sharp in the PRZ and generally occurs in the Brockram and basal sandstones. To the south and west of the PRZ the saline transition zone is more diffuse.

6.68 A good indicator of the rate of groundwater flow through the system is provided by the length of time that the water has been resident in the ground. Information can also be obtained for the residence time of the solutes dissolved in the water. (See Table 6.2 for a description of the geochemical indicators of groundwater residence times.) The best evidence for residence times for water and solutes in the BVG in the PRZ comes from stable isotopes and chlorine-36 data respectively. The stable isotopes (oxygen and hydrogen) together with data from analysis of the noble gases in the water, indicate the water has been recharged (entered the ground) under colder climate conditions, during the Pleistocene (up to 1.6 million years ago). The chlorine-36 data indicate that the chloride in the water in the BVG in the PRZ has had a long residence time, possibly over 1.5 million years. Preliminary helium data also indicate long residence times of similar magnitudes.

6.69 The latest interpretation of the geochemical data is thus indicating:

i. a consistent pattern for the distribution of groundwater types;

ii. all the observed groundwater compositions can be attributed to mixing between four identified groundwater components; and

iii. long residence times for the water and solutes, possibly up to 1.5 million years. This is shown by four independent sources of data: stable oxygen/hydrogen isotopes, noble gases, chlorine-36 and helium data. Evidence of mixing between components, coupled with long residence times suggest low flow of groundwater through the BVG at depth and a high potential for dilution and dispersion occurring in the ground of any residual mobile or long-lived radionuclides from a repository in groundwater that may ultimately reach the surface environment.

Conclusions on Groundwater Flow

6.70 The conclusions reached from the above examination of groundwater flow are thus:

i. the hydraulic conductivity of the BVG is low;

ii. groundwater flow through the BVG is through fractures in the rock;

iii. groundwater flow in and through the BVG is controlled by the flowing fractures, which comprise around 0.5% of the fractures in the BVG;

iv. the network of flowing fractures was largely created some 200 million years ago and has persisted since that time, although changes to individual flowing fractures are likely to have occurred. The persistence of the network indicates a high degree of stability within the system;

v. significant progress has been made in establishing the geological characteristics of the flowing fractures thus providing confidence regarding extrapolation of conditions through the rock mass;

vi. the flowing fractures are linked to form networks of connected fractures through which groundwater can flow. This was deduced initially from the

results of the Short-Term Hydrogeological Testing. Testing carried out during the last eighteen months, particularly the Fracture Network Testing, Cross-Hole Hydraulic Testing and the Borehole RCF3 Pump Test, has indicated that these connections may not be as extensive as had been originally inferred;

vii. a provisional conclusion from the Borehole RCF3 Pump Test is that there appears to be little connection between the BVG and the overlying sandstones;

viii. there is little or no vertical component of environmental head gradient from the likely level of a repository through to the base of the Brockram and, in some parts of the PRZ, on up into the sandstones; and

ix. the geochemical data, and particularly the conclusions on long residence times, are providing independent confirmation of low groundwater flow.

II. DILUTION

6.71 Substantial dilution of radioactivity contained in groundwater that has passed through a repository will be achieved if low flows in the repository host rocks are mixed with higher flows in rocks nearer the surface.

6.72 The evidence of low groundwater flows in the BVG has been presented above. It remains therefore to consider the evidence for the presence of high flows in the sandstones.

6.73 This evidence, again, comes from a variety of sources, as follows:

i. the hydrogeological data, supported by the geochemical results, has led to the identification of a shallow, freshwater regime (Coastal Plain Regime) in which the water has been shown to be chemically distinct from the deeper groundwater and to have been recharged more recently than the saline groundwaters shown to exist at depth (Paragraph 6.62).

ii. porous medium numerical modelling of flow in the sandstone generally endorses the overall hydrogeological concept of an active, relatively fresh, groundwater regime in the upper part of the sandstones. These models are in fair agreement with the measured heads in the sandstone, and confirm that a freshwater flow system exists in the upper part of the Sherwood Sandstone Group (*Nirex Report 524*, Volume 3, Paragraph 6.6, page 6-35 [COR/517]); and

iii. the groundwater heads observed in the sandstones indicate that the upper 150 to 200 metres of the Sherwood Sandstone Group is an active aquifer system (Paragraph 6.55).

III. REMAINING UNCERTAINTIES

Understanding and Prediction of Groundwater System

6.74 Nirex recognises the importance of the groundwater flow regime being well understood and predictable (*PERA*, paragraph 6.3.1 [COR/501]).

6.75 The extensive programme of investigations is indicating a consistent pattern of groundwater conditions. The description of the basic three groundwater

regimes, comprising deep brine, deep saline water and shallow freshwater, have remained essentially unchanged from an early stage in the investigations. In 1992, on this basis of only a limited reconnaissance of the site, the three-regime system was identified in schematic form in *Nirex Report 268 Sellafield Hydrogeology, August 1992 ("Nirex Report 268")* (Figure 3.3) [COR/521]. The regimes were described in more detail in 1993 (Figure 13 of *Nirex Report 525* [COR/505]). It was noted that information from the determination of groundwater chemistry was helping to confirm the pattern of groundwater flow indicated independently by the information on the groundwater pressures and hydraulic conductivity. Finally, as summarised in Paragraphs 6.60 - 6.69 of my evidence, the current interpretation of the groundwater regimes remains essentially unchanged despite the substantial increase in the amount of available data from the site.

6.76 Nirex has designed its investigations to take due account of the features of the site to provide confidence that the significant ones are recognised and characterised. Care is taken to avoid undue reliance on any single technique in the interpretation of the ground conditions. This means that significant features and characteristics of the site are invariably investigated using a range of independent techniques. This provides assurance that these significant features and characteristics are determined with confidence. An example quoted earlier in this section (Paragraph 6.69) was the use of four independent analyses, all of which gave consistent results, for the estimation of residence times for groundwater and solutes. Another example is the conclusion of low groundwater flow through a small sub-set of fractures in the BVG which is based on independent observations arising from Full Sector Tests, flow zone characterisation, mineralogical studies, Short Interval Hydraulic Testing, Fracture Network Testing and the Borehole RCF3 Pump Test.

6.77 The level of detail with which it is now possible to describe the features of the site shows that a high level of understanding of the groundwater conditions has been developed. The basic nature of the groundwater flow system has been established, but uncertainties remain to be addressed in respect of the quantification of flows.

6.78 The prognosis of the site conditions, as presented by Nirex in 1989 when the decision was taken to investigate Sellafield (*PERA*, Section 8 [COR/501]), has been confirmed. As new data are obtained they are fitting into place with previous views about the site that had relied more heavily on judgment.

6.79 The extent to which the groundwater flow regimes can be described using mathematical models is a further aspect related to understanding and predictability. However, it is not adequate simply to be able to describe the groundwater flow system using mathematical models. It is important that the model predictions are compared with independent field observations and experimental measurements. This is the principle of validation described in Dr Holmes' evidence (**PE/NRX/13**, Paragraphs 5.8 - 5.9).

6.80 As recognised by Nirex in 1993, some of the initial groundwater flow models were unable fully to reproduce certain aspects of the independent field measurements (*Nirex Report 524*, Volume 3, page 8-5 [COR/517] and *Nirex Report 525*, page 22 [COR/505])

6.81 Some improvement in the match between models and independent observations is being noted in the new models published in *Nirex 95*

[COR/522]. However, there are still some differences between the calculated and observed salinities and heads.

6.82 The characteristics of the networks of connected fractures in the ground can only be established by direct measurements of the rock in three dimensions on length scales sufficient to cover the intersections and connections of the real fractures. This cannot be achieved without direct access to the rocks underground from the RCF.

Summary of Remaining Uncertainties affecting Groundwater Flow

6.83 A considerable amount of information and understanding exists regarding the site and issues related to groundwater flow. However, as I have identified, there are some remaining uncertainties which currently limit confidence in the assessments of post-closure performance needed to enable a decision to be taken on whether or not Nirex should propose development of a repository.

6.84 Some of these remaining uncertainties can be addressed from continued surface-based investigation; others can be addressed in the laboratory. These are listed in Table 6.3 (a).

6.85 However, although the investigations carried out so far have provided a considerable amount of understanding about the nature and distribution of the flow zones in the Boreholes, there remains uncertainty regarding the conceptual models which we need to develop to describe the way in which these fractures form networks of connected fractures through which groundwater flows. This is because we cannot directly observe or characterise these networks using boreholes from the surface even though we can infer some information about them from the hydrogeological testing we have carried out.

6.86 Investigations from the surface are thus not able fully to address the remaining uncertainties due to the inherent limitations of such measurements made in Boreholes. In particular:

i. the Boreholes are only able to sample the rock over a limited volume defined by the length (or depth) of the hole and its diameter. Many features, such as fractures are thus inadequately sampled. It is known that many of the fractures observed in the rocks at the surface have lengths often measured in metres. The Boreholes are thus unable to provide any substantial information about the variability of fractures at the length scales approaching the lengths of individual fractures; and

ii. although the presence of flow zones can be recognised in Boreholes, and the behaviour of the networks of connected fractures examined by hydrogeological tests (such as the Cross-Hole Hydraulic Testing and the Borehole RCF3 Pump Test), the opportunity does not exist for studying and characterising the flow zones themselves, except at the specific location where they happen to have been intercepted by the borehole. No direct evidence can thus be obtained about their spatial variability and length, and the way they are connected except at the scale of the borehole sample.

6.87 The RCF will allow these remaining uncertainties to be addressed because it will allow the flow zones and the ways in which they form networks of

connected fractures to be directly observed and characterised in the excavations created as shafts and galleries. These will provide observations at length scales very much longer than those provided by the borehole cores. They will also permit the networks of connected fractures to be observed and characterised in three dimensions by permitting access to them both through excavations and through the drilling of short, closely targeted boreholes drilled from the underground excavations. Through testing and monitoring utilising closely spaced and targeted boreholes we will be able to obtain a much more detailed and comprehensive understanding of these networks of connected fractures than is possible using deep boreholes from the surface.

6.88 It was noted in Paragraph 6.40 that many of the responses observed in the Cross-Hole Hydraulic Testing were extremely small and that many were close to the limits of resolution of the monitoring equipment and of a similar magnitude to the natural short-term cyclic fluctuations observed in the monitoring network dataset. These small responses were observed from the effects of drawdowns induced in Borehole 2 of between 100 and 200 metres in head. The drawdowns (reductions in groundwater pressures) induced by the construction of the RCF will be significantly greater (up to 1000 metres) than those which will have been induced on the groundwater system by the existing hydrogeological testing. Such drawdowns will tend to reveal the presence of any connections which exist between the BVG and the overlying sandstones by inducing flow from the sandstones through the Brockram and into the BVG which will be detected by the instrumentation network already installed around the RCF shaft site (Table A.11 in Appendix 1).

7. NATURAL AND INDUCED CHANGES TO THE GEOLOGICAL BARRIER

7.1 It is important to be able to demonstrate that future changes, which may be natural or induced by repository construction, will not create new pathways that would result in unacceptable flows or cause damage to the engineered barriers of the repository that would significantly impair their ability to retain radioactivity.

Natural Changes

Approach

7.2 A geological principle which guides much of the thinking on geological change is that of uniformitarianism: that the present can be used to interpret the past. This principle leads directly to the concept that processes operating at present and in the past will operate in the future, and produce similar results over the timescales of interest to repository safety assessment studies.

7.3 The current approach being adopted by Nirex is to concentrate efforts on observing the effects on the system of past geological and climatic changes. This approach is supported by the *Nirex Review Panel Annual Report, 1994* (section 3.1.1 (b), page 4) [COR/516], which states:

"The approach adopted by Nirex, whereby current efforts are concentrated on observing the effects on the system of past changes to climate, are fully

supported. "

7.4 A wide range of geological, hydrogeological and geochemical studies are being undertaken to develop an understanding of the long-term evolution of the site as a guide to potential future changes. The major components of these studies are:

i. geological studies to determine the history of the development of the East Irish Sea Basin, including history of deposition, burial and uplift (See Section 5) {518};

ii. studies to elucidate the history of the development of the fractures (faults, joints, etc.) {520, SA/95/001};

iii. studies of the Quaternary deposits, particularly with regard to the information they can provide on the history of glaciation and deglaciation, sea level changes and the possible occurrence of recent fault movements {519}; and

iv. palaeohydrogeological studies to establish the way in which the groundwater system has evolved through time {S/95/008}.

7.5 Tectonic and climatic processes are likely to affect any site in the UK over the time periods we need to consider. The issue is therefore one of establishing a rational basis for estimating the impact of these changes so that they can be given appropriate recognition in the assessment of the post-closure performance of a repository.

Age of Faulting

7.6 Traditionally, fault movements were dated indirectly by determining the ages of rocks offset by the faults and the ages of undisturbed, cross-cutting (e.g. dykes or mineral veins) or overlying strata. In recent years, a growing number of techniques have been applied to enable direct dating of fault rocks using a similar approach to that adopted for dating the fracture mineralisation (Paragraphs 6.24 - 6.25).

7.7 Using these new techniques, two groups of fault rocks have been dated, namely:

i. three samples from Fault 200 encountered in Boreholes 2 and 4; and

ii. three samples from Borehole 3 and 4 which shared many features but were markedly different from the first group.

7.8 The samples from the first group gave ages for the fault wall rock ranging from 255 to 315 million years. Fault gouge samples were dated at between 118 and 146 million years and were considered to represent minimum ages for fault activation and reactivation along different planes in the same fault zone.

7.9 An authigenic illite clay in the second group gave a minimum age of 212 million years, possibly representing a period of enhanced tectonic activity during the opening of the East Irish Sea Basin in the Triassic. The minimum age of authigenic illite-smectite clay also in the second group was estimated to be 60 million years. This is not thought to be related to a faulting episode, but may be due to a thermal event at that time in the Tertiary (See Figure 5.1).

7.10 Dating of the fault rocks and studies of the fracture mineralisation, including that associated with the flow zones, thus supports the view that the last major

episode of faulting occurred over 100 million years ago and that the network of flowing fractures has probably persisted in the rocks for around 200 million years. This is not to say that younger fault movements have definitely not occurred. Indeed, geological evidence from surrounding parts of the UK suggest movements may well have continued into the Tertiary and beyond. However, we see no evidence that these younger movements, if they have affected the Sellafield rocks, have caused significant changes to the rocks relevant to the potential of the site to host a repository. Investigations are required in the RCF to examine the rocks at depth for evidence of recent changes, although I do not expect to observe any significant features.

Impacts of Glaciation

7.11 During the latter part of the Quaternary, the British Isles have been glaciated on several occasions. About ten more glaciations of comparable extent are anticipated in the next million years. *The Royal Society, November 1994* (Section 10.1.3 (i), page 156) [COR/605] stated:

"Over the next 10,000 - 100,000 years it is very probable that global climate will change so as to produce glacial or periglacial conditions in the UK, with a lowering of sea level and a major impact on the biosphere. "

7.12 The results of the Quaternary Characterisation studies available so far have indicated that:

i. the area has been glaciated and subjected to changes in sea level over the last tens of thousands of years {519}; and

ii. the Quaternary sediments show evidence of dislocations associated with ice movement (glacitectonic structures). However, despite extensive searching using remote sensing and high resolution seismic surveys, no evidence has been found of tectonic faults having involved both the bedrock and the Quaternary deposits themselves.

7.13 The palaeohydrogeological aspects of the geochemical studies (Paragraph 6.65) have indicated that the deeper freshwater component was possibly recharged in a cold (glacial or periglacial) phase of the Pleistocene, with the shallower component being recharged since that time. However, no evidence has been found to indicate that there has been extensive flushing of the water from depth during the last glaciation (10,000 to 26,000 years ago) since the chlorine-36 and helium data have indicated residence times for solutes in the order of 1.5 million years.

Earthquakes

7.14 This section examines the occurrence of earthquakes in the UK and in the area around Sellafield. On the basis of the effects they have produced, it concludes that, although there is some level of earthquake activity in the area around Sellafield, earthquakes are not expected to have a significant effect on the physical stability of the site in terms of its potential to host a repository.

7.15 Whilst it is important to take due consideration of earthquakes in the assessment of the site, it is equally important to keep such studies in

perspective. The *Nirex Review Panel Annual Report*, 1994 (Section 3.1.1 (a), page 4) [COR/516] stated:

"The Panel holds the view that earthquakes are unlikely to be a major threat to the performance of the Sellafield site. However, because no area of Britain may be considered totally immune, Nirex should maintain a balanced view and focus on establishing whether the site is robust to the effects of earthquakes. This is best achieved through a consideration of the geological record, and details of historical seismicity".

7.16 Nirex have collated a considerable amount of data relevant to the seismicity of the area around Sellafield through the site characterisation programme and seismicity studies. Work is continuing in all areas of study.

7.17 International safety guidelines relevant to the siting of nuclear facilities are used as the basis for the Nirex studies on seismicity of the Sellafield site. *IAEA Safety Standards No 99, Safety principles and technical criteria for the underground disposal of high level radioactive wastes, 1989 ("IAEA Safety Series No 99")* (Criterion 7, page 15, paragraph 4.4.1) [GOV/503] states that:

"The possibility of tectonic, seismic and other disturbances which can create new paths for the transport of radionuclides shall also be carefully evaluated. "

7.18 *IAEA Safety Series 62, Procedures and Data Site Investigations, Design, Construction, Operation, Shutdown and Surveillance of Repositories for Low- and Intermediate-Level Radioactive Wastes in Rock Cavities. Vienna: IAEA, 1984.* (Section 4.5.4, pages 19-20) [NRX/14/1] states that:

"In general, however, underground structures are not so susceptible to seismic disturbances as surface structures. Potential vertical and lateral movements, stresses, and subsurface faulting should be taken into account when developing scenarios resulting in various adverse effects, not only on repository performance, but also on the hydrogeological conditions in the surrounding area. "

7.19 *Euradwaste series No 6, Radioactive waste disposal: recommended criteria for siting a repository. Commission of the European Communities 1992.* (Section III.1, page 5) [NRX/14/2] stated:

"The site shall present a high degree of stability: tectonic movement should not be expected to occur (or to induce significant phenomena) before, e.g. 10000 years, evaluated at regional levels and forecasted from present trends and evidences of events in the past. More generally, the site should be deemed to be stable as long as necessary according to the safety assessment. Seismicity shall be low. Its acceptable level depends on the option and the site, but it shall be shown that tectonic movements are not expected to reach Level 7 on the Richter scale (or an intensity of IX-X in the modified Mercalli scale). "

7.20 *The Royal Society, November 1994* [COR/605] (Paragraph 10.1.2, page 155) stated:

"The mainland of the UK is not close to an active plate boundary and the

evidence from the historical record of the last few hundred years shows that it has been subject to only moderate or small earthquakes (up to about magnitude 5.5) in that time. However, on the timescale of interest to Nirex's post-closure assessment this may not always be the case. Infrequent earthquakes with magnitudes exceeding 6.0 do occur in the interior of plates away from their boundaries, and some of these may be associated with the loading and unloading of ice caps that accompany climatic change. The effects of earthquakes on a potential repository site therefore need to be considered. "

7.21 Nirex has initiated studies to evaluate the nature of the tectonic and seismic disturbance which could affect a repository at Sellafield. The methodology for these studies is in accordance with *IAEA Safety Series 50-SG-S1, Earthquakes and Associated Topics in relation to Nuclear Power Plant siting, A safety Guide, Vienna, 1991* [GOV/508].

7.22 The geological structure interpreted from the extensive site investigation studies has identified the main faults within the area around Sellafield. The identification of faults is important because earthquakes of significant size generally occur on already-existing faults. The identified faults are being characterised and, as described in Paragraphs 7.6 - 7.10, studies to date support the view that the last major episode of faulting occurred over 100 million years ago.

7.23 A seismological database has been assembled for the Sellafield area {SA/95/003}, which is based upon historical records and instrumentally recorded earthquakes. The 1786 Whitehaven earthquake of magnitude 4.7MSA (MSA is the surface wave magnitude assessed from a consideration of the felt area of the earthquake {SA/95/003}) is the most significant earthquake for which records exist in the Sellafield area. Over the last four centuries, at least fifteen earthquakes would have been felt around the Sellafield site although there is nothing in the historical and instrumental records to indicate that any comparable event has occurred near the site since 1786 (See Drawing Nos. 10106 to 10108 in *Nirex Report SA/95/002* [COR/518]).

7.24 Although it was not felt at Sellafield, the 1865 earthquake at Rampside near Barrow is the most damaging earthquake that appears to have occurred in West Cumbria. It was of low magnitude (3.0 MSA) but near surface (probably less than 1 km) and therefore generated relatively high intensities (VII - VIII) over a small area. The earthquake is believed to be unique among British earthquakes in that it caused liquefaction of beach sands with the expulsion of water. There is no reason to suppose that any effects on deep groundwater were involved that would be relevant to the assessment of repository performance.

7.25 Nevertheless, Nirex is examining the risk associated with hydrogeological changes due to seismicity. Palaeohydrogeological studies of the fracture network will provide evidence on how the minerals and their fluid inclusions in the fracture system have evolved. Such studies do, however, require access to the fracture system to provide samples of fault and fracture infill material. To characterise the faults and fractures and to permit suitable and representative sample locations to be selected requires access to the rock mass at depth. This can only be provided in the RCF. The groundwater monitoring

system, together with the Sellafield seismic network and the acoustic monitoring equipment, will provide evidence as to whether changes to the groundwater system occur in association with earthquakes recorded in the local area. As discussed in Paragraphs 6.71 - 6.73, the groundwater system at the Sellafield site provides dilution in the sandstones for any water released from the BVG. Hence, even if some deep water was released in an earthquake this water would be subject to dilution in the sandstones before reaching the surface.

Conclusions on Natural Changes

7.26 Studies related to natural changes to the geological barrier have concluded that:

i. the Sellafield site, like most basement areas, owes its origins to a long geological history. At the Sellafield site this can be traced back some 460 million years. The geological structure has been defined by the investigations (Section 5);

ii. dating of fault rocks and studies of fracture mineralisation support the view that the last major episode of faulting occurred over 100 million years ago and that the flowing fractures are part of a system of fractures that has probably persisted in the rocks for around 200 million years (Paragraphs 7.6 - 7.10);

iii. no evidence has been found of tectonic faults having involved both bedrock and the Quaternary deposits nor has any evidence been found to indicate that there has been extensive flushing of the water from depth within the BVG during the last glaciation (Paragraphs 7.11 - 7.13);

iv. earthquake activity in the UK is low and is not expected to have a significant effect on the physical stability of the site in terms of its potential to host a repository (Paragraphs 7.14 - 7.25); and

v. characterisation of the faults and fractures to provide information on how the fracture system is evolving requires access to the rock mass at depth. This can only be provided in the RCF (Paragraph 7.25).

Changes Induced By Construction

7.27 It is readily appreciated that construction of an underground excavation will have some impact on the surrounding rock. In particular, the redistribution of stress in the rocks in the vicinity of the excavation will result in some changes to the fracture properties and may generate new fractures. This type of change arising from construction is referred to as 'excavation disturbance'. The significance of this is described by Dr Hooper's evidence (**PE/NRX/15**, Paragraphs 6.45 - 6.50).

7.28 Studies to provide estimates of excavation disturbance {NGI Reports 931005-031 and 931005-51} have comprised:

i. characterisation of borehole cores and surface outcrops to derive rock mass parameters;

ii. modelling studies; and

iii. comparison with excavation disturbance measured in other underground openings.

7.29 The conclusions of the studies are:

i. the nature and extent of excavation disturbance likely to develop around an underground excavation is sensitive to variations in rock mass quality and the in situ stress field;

ii. because stresses increase with depth (Table A.13, Appendix 1), depth becomes the most dominant variable affecting excavation disturbance;

iii. the stress field is not uniform in the horizontal direction. Hence constructing an excavation to be either normal or parallel to the maximum horizontal stress direction influences the extent of the excavation disturbance;

iv. although there are variations in predicted excavation disturbance, in general terms the studies have indicated that for the range of likely conditions, excavation disturbance is likely to be represented by an increase in hydraulic conductivity parallel to the axis of the excavation of up to two orders of magnitude extending out for a distance of up to 2 times the excavation diameter; and

v. some modelled excavations demonstrated a tendency for excavation disturbance to be associated with a decrease in radial hydraulic conductivity likely to be associated with a reduction of groundwater inflows.

7.30 Comparison between the extent of excavation disturbance derived from the models and that reported as being measured in the records of the Norwegian Geotechnical Institute indicated a broad consistency between predicted and measured values. However, there are two areas of uncertainty, namely:

i. the modelling of the Sellafield site rocks is based primarily on rock mass characterisation data derived from borehole cores. Estimates of joint continuity are based on data from the surface. There are uncertainties regarding the validity of the extrapolation of the small-scale measured data from the borehole to the large-scale models of likely repository vaults; and

ii. validation of the models has been based upon measurements of excavation disturbance made in other rock types in other geological environments. Uncertainty exists as to whether the BVG will behave in a similar manner to rocks from other sites.

Summary of Remaining Uncertainties Related to Changes to the Geological Barrier

7.31 As explained, a considerable amount of knowledge and understanding exists concerning natural and induced changes to the geological barrier. There are, however, some remaining uncertainties which still need to be resolved and which need to be addressed in the RCF. They comprise:

i. detailed examination of fractures in the rock at depth for evidence of natural changes from associations between the fractures and groundwater flow and mineral formation; and

ii. measurement of responses of the rocks and groundwater conditions to construction.

7.32 Item i. has so far been addressed through the examination of the fractures using boreholes drilled from the surface. This technique is restricted to locations where a borehole happens to encounter a significant feature and limited to the size of the core sample (approximately 100 mm diameter). The RCF will permit significant fractures, once encountered, to be examined in detail in three dimensions through a combination of excavation and targeted drilling. In this way information on such issues as length, continuity, connectivity, orientation and variability in three dimensions can be explored.

7.33 Measurements of excavation disturbance are required (to address item ii. above) to validate the extent to which the models that predict excavation disturbance are valid for the BVG. These measurements can only be made in an underground excavation such as the RCF.

7.34 Other matters that remain to be addressed are the continuing monitoring of earthquakes and acoustic emission from the rocks and investigation of the Quaternary deposits. These can adequately be addressed using surface-based investigation as summarised in Table 6.3 (b).

8. DESIGN AND CONSTRUCTION OF THE REPOSITORY

Introduction

8.1 If a repository is constructed at the site, decisions will be needed to select the depth, location, layout and orientation of the repository vaults. This selection will be influenced by the nature, distribution and dimensions of potentially important structures, such as flow zones, within the rock mass that could control rock quality or groundwater flow. This section of my evidence explains the current understanding of these features and identifies the remaining uncertainties which need to be addressed.

Geological and Hydrogeological Factors Influencing Repository Depth, Location, Layout and Orientation

8.2 The BVG was identified as the potential repository host rock. The position of the top of the BVG was, and is, defined by the contours on the top of the Basement (See Drawing No. 10054 in *Nirex Report SA/95/002* [COR/518]).

8.3 The initial results from Boreholes 2, 4 and 5 suggested the possibility of slightly elevated hydraulic conductivity in the upper 100 metres of the BVG. (EPM 9 in Borehole 2, EPM 6 and 7 in Borehole 4 and EPM 9 in Borehole 5: Drawing Nos. 10133, 10135 and 10136 in *Nirex Report SA/95/002* [COR/518]). This supported a previously developed view that a repository should be located with at least 100 metres of BVG cover.

8.4 The top surface of the BVG falls in elevation towards the west (Figures 5.2 and 5.3). Hence, in order to maintain the nominal 100 metre cover of BVG over a repository, as the repository is moved progressively west it would have to become deeper. The measured rock stresses show a linear increase with depth (Table A.13 in Appendix 1), the temperature increases with depth (20·C at 500

metres depth, thereafter increasing at 25·C per 1000 metres) and the extent of the excavation disturbance likely to develop around a repository is likely to increase with depth. Construction costs will also tend to increase with depth, partly because of the ground conditions and partly because of increased cost of access (deeper shafts and/or longer access drifts). Taking these factors into account, the maximum depth for a repository was taken, for planning purposes, as 1000 metres below ground level, which approximated to 900 metres bOD.

8.5 To provide the nominal 100 metres of BVG cover above a repository, the western limit of a potential repository location is thus defined by the 800 metres bOD contour on the top surface of the BVG (See Drawing No. 10054 in*Nirex Report SA/95/002* [COR/518]).

8.6 The 800 metre bOD contour on the top of the BVG is approximately coincident with the Fleming Hall Fault. This is not only a large fault, with a trace length of 4 km and a maximum throw (at base Permo-Triassic) of 355 metres, but it also forms the eastern limit of the Carboniferous Limestone. The Carboniferous Limestone generally has a higher hydraulic conductivity than the BVG (median value is 5 x 10-8 metres/second) and there is evidence from the borehole core samples that the formation shows enhancement of hydraulic conductivity by solution processes along fractures (*Nirex Report 524*, Volume 3, section 2.3.6, pages 2-10 [COR/517]). There is also the known potential of the Carboniferous Limestone to contain iron ore bodies. The decision was therefore taken to avoid the repository being located close to the Carboniferous Limestone. This factor thus defines the westward and northward extent of the PRZ.

8.7 To the south-east of the Site area the Seascale Fault Zone occurs. This is a major east-south-east trending structure comprising a number of individual faults. Displacements measured at the base of the Permo-Triassic range up to 170 m across an individual fault with the overall throw across the fault zone in excess of 350 metres.

8.8 The current hydrogeological modelling (*Nirex 95* [COR/522]) assumes that both the Fleming Hall and Seascale Fault Zones are significant hydrogeological features with enhanced hydraulic conductivity associated with them. This supports the previous decision that a repository should avoid being positioned immediately adjacent to these two fault zones.

8.9 Thus the position of possible locations for a repository in plan is defined by the extent of the Carboniferous Limestone to the north, by the Fleming Hall fault to the west and by the Seascale Fault to the south. The eastern limit is defined on environmental grounds by the boundary of the Lake District National Park. The boundary of the PRZ as now defined has been refined in detail to reflect current land ownership, but remains essentially as defined above on geological and hydrogeological grounds.

8.10 Having set the above constraints on the margins of the PRZ, the top of the BVG is noted to be at approximately 550 metres bOD in the southern corner of the PRZ. Thus, still maintaining the concept of a normal 100 metres of BVG over a repository, the nominal highest level of a repository is 650 metres bOD. As explained in Paragraph 8.4 above, the nominal lowest level is 900 metres bOD.

8.11 Studies are continuing to select a preferred position for a repository within the

PRZ. Geotechnical modelling {NGI Reports 931005-031 and 931005-51} has enabled some understanding to be gained on the likely sensitivity of the behaviour of repository vaults to variations in depth, layout and orientation of the repository in relation to variations in rock quality. As noted in Paragraph 7.30, there are uncertainties related to this modelling in terms of validating the input parameters for the rock mass and the outputs from the models in relation to the actual behaviour of the BVG.

8.12 The investigations have indicated (Paragraphs 5.6 - 5.14 and 6.20 - 6.21) that the properties of the BVG are variable. Particular characteristics which are emerging are:

i. a relationship between the various members and formations in the BVG and the occurrence of flow zones;

ii. an apparent linear reduction in flow zone hydraulic conductivity with depth; and

iii. the orientation characteristics of the fractures vary with depth and across the PRZ. Structural domains have been identified in which the fractures have similar characteristics.

8.13 A three-dimensional representational model of the PRZ rock mass is currently being developed. This incorporates interpreted geological, hydrogeological, geotechnical and geochemical data to provide a detailed description of the PRZ. It takes as its basis the current geological model of the PRZ which has, in turn, been developed from the integration of borehole data, cross-hole seismic tomography surveys, seismic reflection surveys and potential field data {S/95/005}. Further refinement to the model will be possible on completion of the interpretation of the trial 3-D seismic survey carried out in 1994.

8.14 The model is inevitably based on partial data. However, by taking due regard of the uncertainties inherent in the model and by testing the various alternative interpretations against independent measurements, confidence can be built that the model is an adequate representation of reality.

8.15 The current model of the site incorporates a number of judgments that cannot be adequately tested using data obtained from the surface. Of these, the most important relates to the nature and arrangement of networks of connected flowing fractures in the rock. Their distribution within the rock mass and the extent to which they may be intersected by repository vaults, and hence the extent to which it might be possible to locate vaults to limit the intersections between these networks of connected fractures and the repository vaults are further important considerations.

8.16 The model will be tested against direct measurements in the RCF. Initially, the RCF will test the model in the area of the shafts. Progressively, as galleries are driven out from the shafts and peripheral drilling carried out, the model will be tested in the wider PRZ. The rate at which confidence will be built in the model of the wider PRZ will depend on the extent to which it is found to be an adequate representation of the conditions found in the RCF.

Summary of Remaining Uncertainties Affecting Repository Design and Construction

8.17 In Section 6 of my evidence I showed that the main flow channels in the BVG

are considered to consist of networks of connected fractures. As described in Paragraphs 6.8 - 6.45, it is the characterisation of the flowing fractures and features and, in particular, the way in which these are connected so as to permit the movement of groundwater through the BVG and into the overlying strata that constitutes the principal area of remaining uncertainty.

8.18 There are some further investigations planned to be undertaken from the surface that partially address some of the uncertainties. These are described in Table 6.3 (c). However, in much the same way as explained in Paragraphs 6.83 - 6.88 in relation to groundwater flow and radionuclide transport, remaining uncertainties over the characteristics of the flow zones, and particularly their large-scale characteristics, such as their distribution through the PRZ, that cannot be determined from boreholes, is currently limiting our ability to select an optimum position for a repository. In addition, as explained in Paragraphs 7.31 - 7.34, uncertainties over the extent of excavation disturbance and the relationship between this and variations in rock properties within the PRZ also limits our ability to select the optimum position for a repository.

8.19 These remaining uncertainties can only be addressed through investigations carried out underground in the RCF.

9. CONCLUSIONS

Introduction

9.1 This final section of my evidence draws together the various threads presented earlier into a series of consolidated conclusions. Firstly, I summarise our current understanding of the geology and hydrogeology of the Sellafield site in qualitative terms, recognising that it is only through the process of safety assessment that the suitability of the site can be assessed in relation to regulatory targets. Secondly, I draw together the various remaining uncertainties that exist concerning the geology and hydrogeology of the site that need to be addressed in the RCF.

Summary of Current Understanding of Geology and Hydrogeology

9.2 Nirex has carried out an extensive and systematic investigation of the geology and hydrogeology of the Sellafield site using a wide range of techniques and technical specialists. So far the investigations have been carried out entirely from the surface.

9.3 Studies of the geology of the area have confirmed that the geological sequence and structure are essentially as expected when the decision was taken in 1989 to investigate the site. The investigations have, however, added substantial detail to the understanding of the geology.

9.4 Recognising that the main way in which radionuclides can be transported away from a repository is by flow of groundwater, considerable effort has been directed towards understanding the hydrogeology of the site. The site has favourable characteristics in respect of the two key functions which the geological barrier must achieve (see Paragraph 6.2 above). Firstly, there are

low groundwater flows in the BVG which would host the repository and, secondly, there would be substantial subsequent dilution of any solutes in that water as it joins the active groundwater system in the overlying sandstones.

9.5 These favourable characteristics of the site are being indicated by a range of independent observations. Thus, low flow of groundwater is indicated by measurements of low hydraulic conductivity in the BVG, by observations that flow is through a small sub-set of fractures, and by observations of groundwater chemistry that indicate residence times for water and solutes in the BVG of possibly up to 1.5 million years.

9.6 A provisional conclusion from the Borehole RCF3 Pump Test is that there appears to be little connection between the BVG and the overlying sandstones.

9.7 The groundwater system at the site is increasingly well understood and capable of being described using simple mathematical models supported by a number of independent datasets. Good progress is being made in matching the predictions from these models with independent field measurements.

Summary of Remaining Uncertainties that need to be addressed in the RCF

9.8 However, the surface-based investigations are not able fully to address the remaining uncertainties due to the inherent limitations of measurements made in Boreholes drilled from the surface. Firstly, the Boreholes are only able to sample the rock over a limited volume defined by the length (or depth) of the hole and its diameter. Many features, such as fractures, are thus inadequately sampled. Secondly, the Borehole testing is unable to provide direct evidence concerning the spatial variability and length of the fractures, and the way in which they form networks of connected fractures that control groundwater flow.

9.9 It is the characterisation of the flow zones and, in particular, the way in which these are connected so as to permit the movement of groundwater through the BVG and into overlying strata, that constitutes the principal area of remaining uncertainty

9.10 Uncertainties also exist regarding the extent to which current models reliably predict the extent of excavation disturbance and the variations in rock properties as they impact the selection of the position for a repository.

9.11 These remaining uncertainties need to be addressed before a decision can be made to propose a repository at the site. They can only be addressed through investigations in the RCF.

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PROOF OF EVIDENCE

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GEOLOGY AND HYDROGEOLOGY APPENDICES

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APPENDIX 1: SCOPE OF THE INVESTIGATIONS

A.1. INTRODUCTION

A.1.1 This appendix provides details of the scope of the investigations carried out so far at Sellafield.

A.1.2 The investigations have comprised:

i. geophysical surveys carried out onshore, offshore, from the air and within boreholes;
ii. regional surveys comprising hydrogeological surveys, geological mapping and characterisation of the Quaternary deposits;
iii. boreholes at twenty two locations with a total of 25,712 metres of drilling. The deepest borehole is 1,950 metres deep. Most of the drilling has been carried out to obtain continuous core of the rock penetrated;
iv. the rock cores have been photographed, geologically logged and samples selected for routine and specialist characterisation in the laboratory;
v. hydrogeological testing has been carried out in the boreholes to determine groundwater pressures, rock hydraulic conductivity and other parameters which define how groundwater will move through the rocks;
vi. samples of groundwater have been obtained from the boreholes, analysed and the results corrected for the effects of drill fluid contamination with the aid of chemical tracers added to the drill fluids;
vii. instrumentation has been installed in twenty two boreholes for long-term monitoring of groundwater pressures;
viii. monitoring of earthquakes and acoustic emissions has been carried out;
ix. fractures in the rocks have been characterised both at the surface and in boreholes;
x. geotechnical studies have been undertaken to determine the mechanical behaviour of the rocks; and
xi. the results of the investigations have been interpreted. This has included the development of a range of numerical models.

A.1.3 The locations of the investigations, together with a compilation of the results as a series of maps and drawings are included in *Nirex Report SA/95/002* [COR/518].

A.2. GEOPHYSICAL SURVEYS

A.2.1 A range of geophysical surveys and studies have been carried out at Sellafield. These comprise:
i. onshore seismic reflection surveys;
ii. transition zone seismic reflection surveys;
iii. offshore seismic reflection surveys;
iv. onshore seismic reflection infill surveys;
v. 3-D seismic reflection trial survey;
vi. gravity surveys;
vii. airborne surveys;
viii. electromagnetic surveys; and
ix. miscellaneous surveys to assist in locating faults and for the characterisation of the Quaternary deposits.

A.2.2 Table A.1 describes the purpose of these surveys and identifies the reports which contain the detailed results.

A.3. REGIONAL SURVEYS

A.3.1 Regional surveys have been carried out around Sellafield comprising:
i. regional hydrogeological surveys to study the surface hydrology and near surface hydrogeology;
ii. geological mapping of surface outcrops; and
iii. surveys to characterise the Quaternary deposits of the area.

A.3.2 Table A.2 describes the purpose and scope of these regional surveys and identifies the reports which contain the detailed results.

A.4. DEEP BOREHOLES

A.4.1 Drilling has been carried out at twenty two locations in the Sellafield area (Figures 4.2 and 4.3).

A.4.2 The boreholes have been drilled at a variety of orientations:

i. vertical boreholes are particularly suited for investigating sub-horizontal features such as the boundaries between the main geological formations and sub-horizontal fractures. Most of the deep boreholes drilled by Nirex are vertical;

ii. inclined boreholes (PRZ1 to PRZ3) have been drilled at a constant angle of 20° to 30° to the vertical for the holes. They are used to target specific features at depth from a defined position at the surface and to provide information on sub-vertical features, such as fractures, which are not well investigated using vertical boreholes because the inclination of the borehole is similar to the dip of the feature; and

iii. deviated boreholes are drilled as a vertical hole from the surface and, at a pre-defined depth, are deviated such that the lower part of the borehole are inclined. Inclinations of 10° to 20° from the vertical have been achieved at Sellafield. Boreholes 1/1A, RCF1, RCF2 and RCM3 are deviated boreholes. They combine the benefits of vertical and inclined boreholes in terms of the information they produce on sub-horizontal and sub-vertical features, and can be drilled by the same rigs which have been used for vertical boreholes. Because the rate of deviation which can be achieved is limited by the flexibility of the wireline coring string being used, the inclinations which can be achieved, particularly at depths of around 400 to 500 metres (for example, at the top of the BVG), is less than can be achieved using inclined boreholes.

A.4.3 Most of the drilling carried out by Nirex has been to obtain continuous core which is used for detailed characterisation of the rock penetrated. Geophysical logging is also carried out to determine rock properties and in particular to provide information on the characteristics of the fractures which occur in the rocks. Hydrogeological testing is carried out in the boreholes to determine groundwater pressures and the permeability of the rocks, that is, their ability to transmit water. Testing is carried out during breaks in the drilling and after completion of drilling.

A.4.4 Sampling of groundwater and analysis of samples is routinely undertaken both during and after completion of drilling. Groundwater samples are variably contaminated with drilling fluid. The analytical results are corrected, whenever possible, to estimate true groundwater compositions. This is achieved by adding a chemical tracer to all drilling fluids at a fixed concentration such that, by determining the level of tracer in any groundwater sample, the extent of the drilling fluid contamination can be determined and the necessary corrections applied to determine true groundwater compositions. Lithium (as lithium chloride), maintained at 1000 parts per million (ppm) ± 20 ppm, was used in all boreholes except Borehole 1/1A (no tracer used), Boreholes PRZ1-PRZ3 and Borehole 9. In these latter boreholes iodide (as potassium iodide, maintained at 100 ± 4 ppm), was used. The change to iodide was made for two main reasons:

i. to permit better control of determinations of chloride levels in the near surface fresh and brackish waters; and

ii. to permit detection of possible cross-flow of water containing lithium from adjacent boreholes which had been drilled with the lithium chloride tracer.

A.4.5 Corrections for drill-fluid contamination are carried out using the Tracer Regression Analysis Program which mathematically subtracts the contamination indicated by the tracer. Samples with the lowest contamination of drilling fluid yield data with the highest reliability. Samples with contamination levels of less than 1% have been obtained from many locations. Sample quality is assessed for each sample tested and is reported as part of the test data. It is not possible to use these correction methods for handling non-linear contamination effects, such as occur for pH, redox and carbon-14 measurements.

A.4.6 In commenting upon the geochemical sampling, *The Royal Society, November 1994* (Section 6.5, page 105) [COR/605] stated:

> *"In extracting water from boreholes, it is vital to assess the extent to which samples have been contaminated by fluids used in drilling. Long-term sampling from monitored boreholes is the most effective way to evaluate the state of contamination. In recent hydrogeological well tests, contamination from drilling mud (as evidenced by routinely added lithium chloride tracer, and by contaminant tritium), has been accurately documented and reduced to less than 1% in a*

significant (and increasing) proportion of samples. Nirex have thus demonstrated a capability to obtain high quality samples from existing boreholes."

A.4.7 The completed boreholes are also used for specialist testing programmes. Examples include cross-hole seismic tomography and Cross-Hole Hydraulic Testing described respectively in Paragraphs A.6.3 to A.6.5 and Section A.7.3. A major programme of pump testing was undertaken in 1995 to measure the responses of the groundwater system over a wide area to pumping from a central borehole.

A.4.8 In the area of the PRZ, Nirex was able to locate the Boonwood Borehole and Holmrook 13 Borehole drilled by others several decades ago for mineral exploration purposes. These boreholes have been refurbished and instrumented to supplement the groundwater monitoring system installed in the Boreholes.

A.4.9 Table A.3 lists all these boreholes, describes their objectives, depths and orientations and indicates where more detailed information on the results obtained from them can be found.

A.5. CORE DESCRIPTION AND CHARACTERISATION

A.5.1 The cores obtained from the boreholes are photographed and geologically logged at the drill site. Samples required for specialist testing are taken as soon as possible after removal of the core from the borehole and preserved to retain their moisture content and pore fluids. After completion of the on-site logging activities, further specialist examination of the cores is undertaken, and samples are selected for routine and specialist characterisation in the Core Characterisation Programme.

A.5.2 Table A.4 summarises the scope of the testing included in the Core Characterisation Programme, and Table A.5 identifies the sources of information on the detailed test results.

A.6. BOREHOLE GEOPHYSICS

Wireline Logging

A.6.1 Wireline geophysical logging tools are instruments which are run up and down boreholes on a cable to gather geological and hydrogeological data. They were first developed in the oil industry and are now technologically advanced instruments which are used for a range of purposes. Wireline logs are run as a routine part of the testing of each of the deep boreholes.

A.6.2 Table A.6 gives more information on the details of the individual wireline tools used in the Boreholes and the information which they provide.

Seismic Tomography Surveys

A.6.3 Seismic tomography is a form of interpretation of cross-borehole seismic surveys which has been used to extend knowledge of the structure of the rocks away from the deep boreholes.

A.6.4 An initial survey between Boreholes 2 and 4 was carried out in 1993. Following interpretation of the results and confirmation that the technique was suitable for use in the Sellafield geological conditions, surveys were carried out in 1994 between the following pairs of boreholes; Boreholes 2 and 5, RCF1 and RCM3, RCF2 and RCM3, 5 to RCF3, 2 to RCF3 {S/94/007}.

A.6.5 The results of the tomography surveys have been integrated with other information from the boreholes, seismic reflection surveys carried out from the surface, vertical seismic profiling and surface geological mapping to provide added confidence in the geological structure around the proposed RCF.

Vertical Seismic Profiling

A.6.6 Vertical seismic profiling surveys are carried out in the Boreholes to provide a link between the information produced by the wireline logging and the seismic data from the regional geophysical surveys carried out from the surface. Seismic waves, generated at the ground surface, are recorded in the Boreholes using receivers which are moved up and down the borehole. The information from these

surveys is used both to assist in the interpretation of the regional seismic surveys and to provide information on the locations of faults that occur between Boreholes.

A.7. HYDROGEOLOGICAL TESTING

A.7.1 Hydrogeological testing is carried out as a routine part of the drilling and testing of each of the deep boreholes. There are two categories of testing; short-term testing carried out during or shortly after drilling operations, and long-term testing carried out after drilling has been completed.

A.7.2 The forms of short-term testing adopted comprise Environmental Pressure Measurements, Full Sector Tests, and Discrete Extraction Tests.

A.7.3 The longer-term testing, often referred to as Post Completion Testing, has included:

i. long-term Discrete Extraction Tests targeted on specific features within a borehole;

ii. Fracture Network Testing;

iii. Short Interval Hydraulic Testing;

iv. Cross-Hole Hydraulic Testing; and

v. large scale pump test centred on Borehole RCF3.

A.7.4 Tables A.7 and A.8 respectively give more information about short-term hydrogeological tests and post completion testing.

A.8. GEOCHEMISTRY STUDIES

A.8.1 Groundwater samples have been obtained from a variety of sources for geochemical analysis: from the deep boreholes, from springs, seepages, rivers and rainfall samples from the surface, together with other samples, such as from the drilling fluids and water supplies for control purposes.

A.8.2 Groundwater samples obtained from boreholes are corrected for drill-fluid contamination as described in Paragraphs A.4.4 to A.4.5.

A.8.3 Samples from the deep boreholes have been obtained using downhole samplers and by sampling at the surface.

A.8.4 Table A.9 lists the range of analyses included in the geochemical studies. Table A.10 identifies the sources of information on the results of the chemical analyses.

A.9. GROUNDWATER PRESSURE MONITORING

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A.9.1 Groundwater pressures are being monitored in most of the Boreholes {S/94/006} by the installation of specially configured instrumentation. Instrumentation has been installed in twenty two Boreholes.

A.9.2 The details of the groundwater pressure monitoring system are shown in Table A.11. This table lists the following information for each borehole in which instrumentation has been installed:

i. number of monitoring zones: these are subdivided into primary zones (sections of the borehole containing identified zones of interest based on an assessment of geological and hydrogeological information) and secondary zones (sections of borehole between the identified primary zones);

ii. number of pumping ports: these are devices that permit fluids to be extracted or injected. They are provided to permit the collection of water samples for geochemical analysis;

iii. number of MOSDAX probes: a string of probes fitted with transducers for recording pressures, at pre-determined time intervals, are being installed in all the boreholes. These are the MOSDAX probes. The transducer output is recorded at 2 minute intervals in the boreholes within the PRZ and at 30 minute intervals elsewhere. The probes are installed in the primary zones, plus, in the RCF/RCM Boreholes, some secondary zones are also monitored; and

iv. summary drawing numbers: the outputs from the monitoring network have been summarised on a borehole by borehole basis in a series of drawings in *Nirex Report SA/95/002* [COR/518]. The number of the drawing for each borehole is listed. These drawings contain information on the locations of flowing features, locations of monitoring zones, results of measurements of hydraulic conductivity, calculated groundwater heads and groundwater density data. The monitoring data, as environmental heads, is plotted against time for the full period for which information is available. Wherever possible, changes in head associated with specific periods of testing or other induced effects, such as drilling operations, are identified and labelled. The drawings thus present a complete record of all changes in groundwater pressures which have been recorded by the monitoring network.

A.10. ACOUSTIC EMISSION MONITORING

A.10.1 The acoustic noise emitted by the rocks as they are subjected to small changes in stress, due to natural movements or as can be caused by drilling or hydrogeological testing, can provide valuable information on the extent of the deformations occurring in the rocks, the spatial distribution of these deformations and their variations with time. Triaxial geophone sondes are currently deployed in Boreholes RCF1 and RCM3, and a temporary hydrophone has been installed in Borehole 5. They have been used to monitor the rock stress effects of the Borehole RCF3 pump test.

A.10.2 Planning of future work at Sellafield is being supported by collaborative research being undertaken into acoustic emission monitoring of excavation disturbed zones at the Äspö Hard Rock Laboratory in Sweden. That work has drawn upon experience from similar studies in AECL's Underground Research Laboratory in Manitoba, Canada.

A.11. EARTHQUAKE STUDIES

A.11.1 Information on the occurrence of earthquakes in and around the Sellafield area has been collected from three sources: from historical records, from instrumental records derived from seismographs in Britain and north-west Europe, and from the British Geological Survey Cumbrian Microseismic Network {SA/95/003}.

A.11.2 The results from the Cumbrian Microseismic Network comprise records of seismic events (down to local magnitude £ 1 M_L) detected within a radius of approximately 60 kilometres of Sellafield using a network of eight stations, complemented by existing British Geological Survey seismograph stations. The network stations are located in Cumbria, Lancashire, the Isle of Man and in southern Scotland. The network commenced operating in September 1992.

A.12. FRACTURE STUDIES

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A.12.1 Studies of fractures in rocks have formed an important part of the geological and hydrogeological studies at the Site. They comprise:

i. remote sensing studies;

ii. outcrop mapping;

iii. characterisation of fractures from borehole cores;

iv. characterisation of fractures from wireline log data;

v. structural domain studies; and

vi. fracture mineralisation studies.

A.12.2 Table A.12 lists the studies, their purpose and scope, and indicates where the detailed data arising from the studies are reported.

A.13. GEOTECHNICAL STUDIES

A.13.1 Geotechnical studies are required to determine the mechanical behaviour of the rocks, particularly in relation to developing an understanding of how the rocks respond to the excavation of shafts and tunnels as an input to the design of a possible repository at the site.

A.13.2 Table A.13 describes the scope of the studies and indicates where the results are reported.

A.14. INTERPRETATION AND MODELLING

A.14.1 The data obtained from the studies and measurements are interpreted to provide an understanding of the geological and hydrogeological conditions at the site that may influence its potential to host a repository. This interpretation incorporates the development of a range of numerical models to assist in understanding the site and with the design and interpretation of individual tests.

A.14.2 Interpretation is undertaken in a variety of ways; initially to interpret the results and draw conclusions from individual studies or measurements, and subsequently, by integration of the results and conclusions to establish an understanding and to draw conclusions related to the overall characteristics of the site.

A.14.3 Interpretation and modelling have involved the efforts of a wide range of technical specialists, some working on specific aspects of the results, others more concerned with integrating the results and conclusions from a range of specialist studies.

Table A.1: Regional Geophysical Surveys

Type of Survey	Remarks	Factual Report (Nirex Report Number)
Onshore Seismic Reflection Survey No. 1	Initial survey in 1988 to provide information on geological structure at depth.	{BGS Report DP/88/9}
Onshore Seismic Reflection Survey No. 2	Extension of Survey No. 1	{110}
Onshore Seismic Reflection Survey No. 3	Regional survey. Seismic sections produced from processed data interpreted in terms of geological structure. Contoured depth maps produced for the main geological horizons.	{110}
Transition Zone Seismic Reflection Survey No. 1	To provide linkage between onshore and offshore seismic data. Data used for extension of mapping of geological structure.	{110}
Transition Zone Seismic Reflection Survey No. 2	Extension of area covered by Survey No. 1 to provide linkage between onshore and offshore seismic data	{110}
Offshore Seismic Reflection Surveys - Purchase of commercially available data.	Data from three offshore boreholes (112/25a-1, 112/30-1 and 113/26-1) also purchased and used to calibrate the interpretation of the acquired seismic lines.	
Offshore seismic survey - acquired from others	Survey data acquired from British Nuclear Fuels plc and British Geological Survey to supplement data acquired from Nirex commissioned surveys.	
Offshore seismic reflection surveys - Commissioned by Nirex	Surveys carried out to extend mapping of main geological formations and for extension of depth maps into offshore area.	{110}
Onshore seismic reflection infill surveys	Seismic surveys carried out with closer line spacing to provide added detail of geological structure. Utilised dynamite source, with high frequency lines using airgun source	{145}
3-D Seismic Reflection Trial Survey	To determine whether technique was applicable to the PRZ investigation. 3-D surveys are carried out with closely spaced survey lines and are interpreted to provide a higher resolution interpretation of geological structure at depth than is possible using 2-D surveys along widely spaced lines.	{622}
Gravity surveys	Gravity surveys are interpreted to provide supplementary information to assist in the interpretation of the three-dimensional geological structure of the area. Data obtained from national surveys, existing regional surveys and from Nirex commissioned surveys.	{110} {145}
Airborne survey No. 1	Regional survey. The high level surveys were used to locate regionally significant geological structures. The low level surveys were used to assist with geological interpretation, particularly with regard to interpretation of near-surface geological structure and the identification of faults and lineations.	{110}
Airborne Survey No. 2	The thermal infra-red imaging survey was undertaken as a part of the regional hydrogeological studies and was designed to assist in the location of groundwater springs and discharges.	{142} {499}
Electro-magnetic survey No. 1	The first trial evaluated the transient electromagnetic and magnetotelluric methods and acquisition parameters to establish the feasibility of the techniques and to help in the design of Survey No. 2.	{110}
Electro-magnetic Survey No. 2	A second trial was a controlled source audiomagnetotelluric survey. The survey was designed primarily to provide information on the three dimensional configuration of the saline transition zone at depth and to assist in planning of subsequent surveys in four areas: the zone west of the PRZ, the Seascale Fault Zone, the recharge zone and the PRZ.	{620}
Trial geophysical surveys carried out to assist in the location of faults	The objective of the trial was to define the most appropriate techniques for determining the fault pattern, under Quaternary cover, over the remainder of the	Not yet reported

within the Permo-Triassic sandstone bedrock of the PRZ	PRZ area.	
Characterisation of Quaternary Deposits	A range of geophysical techniques have been used to assist in the characterisation of the Quaternary deposits around the area.	Not yet reported

Table A.2: Regional Surveys

Type of Survey	Description	Remarks	Factual Report (Nirex Report Number)
Regional Hydrogeological Surveys	Regional hydrogeological investigations are targeted specifically at the surface waters and shallow (to depths of up to 500 metres) groundwater regime. The primary objective is to provide the information necessary to develop the understanding of the regional water balance, and in the context of developing this understanding, to identify and establish key sites for the long term monitoring of hydrological and hydrogeological parameters such as climate, streams and springs and groundwater heads. The study area covers the surface catchments of the River Calder and River Bleng extended to include the groundwater catchments associated with these surface water catchments. These extensions comprised: To the north, the mine workings of Florence, Beckermet and Haile Moor which historically have been, and currently are, zones of major groundwater abstraction. To the south to include an area potentially influenced by the presence of thick drift deposits.	(i) Identification and preliminary characterisation (geology, flow and chemistry) of groundwater springs (ii) Selection of 16 representative springs for long term monitoring of flow and water chemistry. (iii) Airborne thermal infra-red survey to assist in the location of springs, particularly along the coastal strip of the study area.(iv) Identification of 144 possible locations on streams and rivers where spot river gauging could be carried out. (v) Spot river gauging at 43 sites, carried out over a 2 week period in August 1992. (vi) Establishment of eleven sites for routine river gauging. The gauging was carried out on a weekly basis commencing March 1993. Additional sites were subsequently added such that by the end of December 1993 sixteen sites were routinely gauged. The number of sites routinely gauged has now risen to nineteen. (vii) Monitoring of data from existing meteorological stations in the area. (viii) Provision and monitoring of one additional meteorological station and five additional rain gauges. (ix) Collection and synthesis of available data on the impact of existing mine workings on the hydrogeological regime of the Sellafield area and use of the mine records as a source of information on the geological controls of groundwater movement.	{142} {233} {499}
Regional Hydrogeological Surveys (continued)		(x) Studies of the influence of human activities in the hydrogeological conditions in the Sellafield area. Groundwater abstraction and the influence of farming on	(See above)

		shallow groundwater chemistry have been particular aspects investigated. (xi) Collation of data from approximately 1500 existing boreholes in the Sellafield area. These studies formed the basis for selecting the Boonwood and Holmrook 13 boreholes for refurbishment and installation of instrumentation for long-term groundwater monitoring.	
Geological Mapping	During 1990, the British Geological Survey (BGS) was commissioned to carry out geological mapping around the Sellafield area to re-map the solid geology (excluding the drift deposits) in the area covered by the BGS Gosforth and Bootle 1:50,000 scale geological map sheets (37 and 47), together with an area in the south of the Whitehaven sheet (28). Based on this work, BGS were commissioned to prepare a compilation map of solid geology of a larger area encompassing the western part of the Lake District.	The mapping was carried out based upon re-mapping of rock exposures and a new interpretation of available sub-surface data (mine plans, borehole data, geophysical data).	{BGS WA/94/04C}
Quaternary Studies	These studies are related to the sediments (glacial, marine and lake-deposits) laid down during the Quaternary period and to the erosion and other processes which may have occurred. The studies are being carried out to meet three objectives: (i)To reconstruct the geological history of the Quaternary history of the area to assist in developing an understanding of possible future geological evolution of the site. (ii) To provide background information of use in modelling the hydrogeological regime, recognising the control over recharge and discharge from the near-surface hydrogeological regime exercised by the Quaternary sediments. (iii) To examine suitable sites for evidence of possible recent fault movements.	Much of the initial work on the Quaternary comprised a series of desk studies which relied heavily on previously published data. Subsequent work has involved the interpretation of borehole and geophysical data to prepare maps showing the thickness of drift and contours on rockhead. The work has included the deposits occurring both onshore and offshore. In 1994, the characterisation work was extended to include the cleaning up of existing exposures and excavation of trial pits for detailed logging, sampling and testing. In 1995 work has commenced on a series of shallow boreholes, generally less than 50 m depth, to characterise further the Quaternary deposits.	{519} {768}

Table A.3: List of Nirex Deep Boreholes

Borehole No.	Depth (metres below Rotary Table)	Orientation	Objectives	Factual Report (Nirex Report Number)	Summary Drawing Numbers in *Nirex Report SA/95/002* [COR/518]

1/1A	1189	Deviated	Reconnaissance	{106}	10132, 10156, 10180
2	1610	Vertical	Reconnaissance	{107}	10111, 10133, 10157, 10181
3	1950	Vertical	Reconnaissance	{108}	10134, 10158, 10182
4	1260	Vertical	Reconnaissance	{109}	10112, 10135, 10159, 10183
5	1260	Vertical	Initial pattern to obtain understanding of geology and hydrogeology.	{371}	10113, 10136, 10160, 10184
7A	1010	Vertical	Initial pattern to obtain understanding of geology and hydrogeology.	{307}	10114, 10137, 10161, 10185
7B	471	Vertical	Initial pattern to obtain understanding of geology and hydrogeology.	{308}	10115, 10137, 10161
8A	1000	Vertical	To investigate recharge area	{143}	10116, 10138, 10162, 10186
8B	245	Vertical	To investigate recharge area	{143}	10117, 10138, 10162
9A	500	Vertical	To investigate recharge area	{618}	10139, 10163
10A	1608	Vertical	Initial pattern to obtain understanding of geology and hydrogeology.	{326}	10118, 10140, 10164, 10188
10B	252	Vertical	Initial pattern to obtain understanding of geology and hydrogeology.	{366}	10118, 10140, 10164
11A	1170	Vertical	To investigate sequence of rocks in area of expected greater Permo-Triassic cover to the south of the Seascale Fault Zone.	{370}	10119, 10141, 10165, 10189
12A	1150	Vertical	Initial pattern to obtain understanding of geology and hydrogeology.	{335}	10120, 10142, 10166, 10190
13A	1740	Vertical	To investigate area of thick Permo-Triassic cover to the south of the PRZ.	{333}	10143, 10167, 10191
13B	296	Vertical	To investigate area of thick Permo-Triassic cover to the south of the PRZ.	{333}	10121, 10143, 10167
14A	873	Vertical	Initial pattern to obtain understanding of geology and hydrogeology.	{334}	10122, 10144, 10168, 10192
RCF1	1150	Deviated	To investigate area of RCF and permit installation of groundwater monitoring instrumentation	{500}	10123, 10145, 10169, 10193
RCF3	990	Vertical	To investigate area of RCF. Borehole down centreline of proposed South Shaft.	{502}	10147, 10171, 10195
RCM1	990	Vertical	To investigate area of RCF and permit installation of groundwater monitoring instrumentation	{553}	10125, 10148, 10172
RCM2	990	Vertical	To investigate area of RCF and permit installation of groundwater monitoring instrumentation	{554}	10126, 10149, 10173
RCM3	1035	Deviated	To investigate area of RCF and permit installation of groundwater monitoring instrumentation	{555}	10127, 10150, 10174
PRZ1	235 (To be deepened)	Inclined	To investigate Fault 1 at contact between sandstones, Brockram and BVG.	{607}	10151, 10175

PRZ2	560	Inclined	To investigate Fault 2 at contact between sandstones, Brockram and BVG.	{608}	10128, 10152, 10176
PRZ3	775	Inclined	To investigate Fault 1 at contact between sandstones, Brockram and BVG.	{609}	10129, 10153, 10177, 10201
Holmrook 13	524	Vertical	Existing borehole refurbished, logged and groundwater monitoring string installed.	Not yet reported	10130, 10154
Boonwood	545	Vertical	Existing borehole refurbished, logged and groundwater monitoring string installed.	{625}	10131, 10155

Table A.4: Core Characterisation and Description - Activities and Component Tests

Activity	Objective of testing	Component Tests
Lithostratigraphical Core Logging	To supplement the geological information on the rock cores.	
Core Orientation and Depth Correction	Using the wireline log data, to provide absolute orientations of fractures in the core and to provide accurate depths of core samples.	
Hydrogeological Core Analysis	To determine hydrogeological properties of core samples.	Gas permeability Permeability to brine or water Porosimetry Pore Volume Compressibility
Bulk Rock Petrography and Geochemistry	To assist in the detailed characterisation and identification of the rock types encountered in the cores.	Thin section optical petrography Reflected light microscopy Cathodoluminescence microscopy Scanning electron microscopy Dispersive x-ray microanalysis Electron microprobe analysis X-ray diffraction Thermal analysis Heavy mineral analysis Whole rock chemical analysis Rare Earth Element Analysis
Fracture Petrography and Geochemistry	To provide detailed information on the characteristics of the minerals which occur within the fractures in the rock.	Thin section optical petrography Reflected light microscopy Cathodoluminescence microscopy Scanning electron microscopy Dispersive x-ray microanalysis Electron microprobe analysis Fluid inclusion studies Stable isotopes (Carbon, Oxygen, Sulphur and Strontium) Fracture logging
Geotechnical and Geophysical Testing	To characterise the mechanical properties of the rocks.	Saturated density Dry density Grain density Saturated water content Effective porosity Slake durability Swelling index Uniaxial compressive strength Indirect tensile strength -

		Brazilian method Strength under triaxial compression Elastic constants under triaxial confinement Thermal conductivity Specific heat Thermal expansion coefficient Compressional and shear wave seismic velocity Magnetic susceptibility Remnant magnetism Resistivity
Core Pore Fluid Extraction and Analysis	Fluids are extracted from the pores in the rock for subsequent chemical analysis in order to supplement the hydrochemical data obtained from analysis of water samples obtained from the boreholes.	

Table A.5: Sources of Information on Core Characterisation

Borehole Number	Litho-stratigraphical core logging	Hydrogeological core analysis	Bulk rock petrography and geochemistry	Fracture petrography and geochemistry	Geotechnical and geophysical testing	Core pore fluids	Summary Rock Property Drawings in *Nirex Report SA/95/002* [COR/518]
1/1A	{106}	{106}	{106}	{106}	{106}		10156
2	{184}	{181} {182} {199}	{204} {734}	{542}	{201} {209}	{202} {210}	10157
3	{195}	{193}	{216} {733}	{641}	{222} {228} {229}	{213}	10158
4	{196}	{194}	{224}	{643}	{528}		10159
5	{205}	{200} {208}	{225} {538}	{651}	{529} {530}		10160
7A/B	{203}	{211} {212}	{217} {536}		{531} {533} {534}		10161
8A	{638}						10162
9A							10163
10A/B	{219}	{226}	{652}				10164
11A	{532}						10165
12A	{220}	{629}			{635}		10166
13A/B	{632}						10167
14A	{548}						10168
RCF1	{537}						10169
RCF2	{539}						10170
RCF3	{541}	{630}			{636}		10171
RCM1							10172
RCM2	{554}				{634}		10173
RCM3							10174
PRZ1							10175
PRZ2	{650}						10176
PRZ3	{646}						10177

Table A.6: Geophysical Wireline Logging Tools and their Application

Tool	Measurements Made	Application

Acoustic Telescanner	Produces down-hole image of sides of borehole	Locations and orientations of fractures
Borehole Televiewer	Produces down-hole image of sides of borehole	Locations and orientations of fractures
Borehole Geometry Log	Borehole size, shape and orientation	Ensures images are correctly oriented with respect to north
Casing Collar Location	Sonic resonance	Locates steel casing installed in boreholes to facilitate drilling
Ultrasonic Imager Tool Cement bond log Variable density log	Sonic and ultrasonic pulses	Provides information to assess the integrity of cement casings installed in the borehole to facilitate drilling.
Temperature	Temperature	Aids detection of groundwater inflows
Electromagnetic Propogation Tool	Phase shift and alteration of a sonic wave	Assists in determining rock types
Electrical conductivity	Electrical Conductivity	Aids detection of groundwater inflows
Dipole Sonic Imager	Sonic travel times and Stonely wave mode	Assists in determining rock types and detects open fractures
Gamma Ray	Radioactivity	Assists in determining rock types. Also used to provide depth control for other logs
Natural Gamma Ray Spectrometry Log	Gamma ray spectroscopy	Assists in determining rock types.
Geochemical Logging Tool	Concentrations of 12 elements (Al, Ca, Cl, Gd, H, Fe, K, Is, S, Th, Ti, U)	Determines mineralogy and assists in determining rock type
Litho-Density Log	Bulk density measurements and porosity analysis	Identifies rock type and fractures
Fullbore Formation Micro Imager (Formation Micro Scanner is older, lower resolution version)	Produces high resolution electrical resistivity image of borehole walls	Identifies fractures. Used for determining absolute orientation of selected fractures
MicroSpherically Focused Log Dual LateroLog	Electrical resistivity	Assists in identifying rock types and fractures. Determines Formation Fluid Resistivity
Compensation Neutron Log	Porosity	Determines porosity in sedimentary rocks
Auxiliary Measurement Sonde	Temperature, pressure, borehole fluid salinity	Used to provide calibration data for other logs

Table A.7: Short Term Hydrogeological Tests

Type of Test	Description
Environmental Pressure Measurements	Environmental Pressure Measurements are tests carried out at specific intervals during the drilling of a borehole and involve interruption to drilling operations. The tests comprise isolation of a nominal 50 metre long section at the base of the borehole. Water is removed from the test section to reduce the pressure in the test section, after which the pressure recovery is monitored for an 8 or 16 hour period. The pressure recovery data is interpreted to provide estimates of the environmental pressure and hydraulic conductivity of the rock within the section. Environmental pressure is converted into equivalent freshwater and environmental heads based upon the density of freshwater and the interpreted vertical groundwater density distribution derived from measured variations in groundwater salinity. Geochemical samples may be taken from the borehole as part of the test.
Full Sector Tests	A Full Sector Test is carried out over the full length of a borehole, often in a series of stages. Fluid (mixture of drilling fluid and groundwater) is removed from the borehole to reduce the head in the borehole by around 200 m to 400 m, thereby inducing groundwater flow into the hole from the surrounding rock. Since the salinity (and hence the electrical conductivity) and the temperature of the groundwater is different from the salinity and temperature of the fluid in the

	borehole, points of groundwater flow are identified from the results of logging incorporating differential temperature, fluid conductivity and spinner flow meter logs for the full depth of the hole. The points of groundwater inflow are termed 'Flow Zones'; their characterisation forms an important part of subsequent hydrogeological testing (See Section 6 of Proof of Evidence).
Discrete Extraction Tests	A Discrete Extraction Test is carried out over a selected section of a borehole to characterise the hydrogeological properties of a single fracture or group of fractures which have generally been identified from interpretation of a Full Sector Test. The section of the borehole selected for testing is isolated using a pair of inflatable packers and water is removed from the test section, following essentially the same procedure as for an Environmental Pressure Measurement. This stage of the test is followed by a period of fluid extraction. Fluid samples are collected and monitored at the surface for tracer levels (to determine level of drill-fluid contamination) and fluid conductivity. When the level of drill fluid contamination has reduced to an acceptable level, generally less than 5%, or has reached a static level, a series of downhole, pressure controlled groundwater samples are collected for subsequent analysis.

Note: Results shown on Borehole Summary Drawings (Drawing Nos. 10132 to 10155) in *Nirex Report SA/95/002* [COR/518].

Table A.8: Post Completion Hydrogeological Testing

Type of Test	Description	Results contained in Nirex Report Number:	Summary Drawing Number in *Nirex Report SA/95/002* [COR/518]
Discrete Extraction Tests targeted on specific features within a borehole	Procedure as for short term testing, but generally with longer duration of testing, typically days or weeks rather than hours.	{383} {387} {597}	Note (1)
Fracture Network Testing	The Fracture Network Testing was carried out in Borehole RCF3. A test phase involved the isolation of a 20 metre long test section and of four twenty metre monitoring sections, two immediately above the test section and two below it. Pumping was carried out from the central test section and the responses to pumping monitored on a continuous basis in the sections above and below. The test unit was then progressively moved to provide complete coverage of the section of the borehole within the Borrowdale Volcanic Group which was being characterised. The objective of the testing was to provide information on the extent of the connectivity of the flowing fractures within the borehole having previously identified them from the Full Sector Tests and characterised them using Environmental Pressure Measurements and Discrete Extraction Tests. By using 20 metre long test sections, as compared to the 50 metre long sections used for the Environmental Pressure Measurements, the tests were designed to provide information on the effects of scale of measurements on the determination of hydrogeological parameters of the fracture system.	{384}	10089
Short Interval Hydraulic Testing	The Short Interval Hydraulic Testing comprised testing of on hundred short sections of borehole (1-2 metres in length) to assess the extent to which water moves through the Borrowdale Volcanic Group through large numbers of small fractures rather than through the rock matrix and/or through the identified flowing features. The testing was carried out in the Borrowdale Volcanic Group in Borehole RCF3.	{386}	10089
Cross-Hole Hydraulic Testing	Cross-Hole Hydraulic Testing has been carried out between Boreholes 2 and 4. The objective of this testing was to characterise the flowing features within Borehole 2 and to establish the connectivity of these features both within the borehole (Borehole 2) and with a neighbouring borehole (Borehole 4). The programme of testing comprised seven periods of pumping from	{381} {722}	10090

	individual discrete sections of Borehole 2, each of which contained identified flowing features, whilst monitoring zones above and below the pumped section (as for the Fracture Network Testing) and whilst monitoring zones in the adjacent Borehole 4 using the installed groundwater monitoring string. Boreholes 2 and 4 are approximately 120 metres apart. The rock between Boreholes 2 and 4 had previously been characterised by cross-hole seismic tomography.		
Large Scale Pump Test centred on Borehole RCF3.	The RCF3 Pump Test is a programme of tests carried out by pumping from sections of Borehole RCF3 covering each of the three main units: the St. Bees Sandstone, the Brockram and the BVG. The responses of the groundwater system resulting from the pumping are being recorded using the monitoring network (see Table A.11 for details).	{624}	10092

Note 1: Results shown on Borehole Summary Drawings (Drawing Nos. 10132 to 10155) in *Nirex Report SA/95/002* [COR/518].

Table A.9: Geochemical Studies - Range of Analyses on Groundwater Samples

Category of Analyses	Species
General	Electrical Conductivity pH, Eh (reduction-oxidation potential), alkalinity (total and carbonate)
Anions	Sodium, potassium, calcium, magnesium
Cations	Chloride, sulphate
Carbon	Total inorganic carbon (TIC), Total organic carbon (TOC)
Trace cations	Manganese, strontium, barium, aluminium, silicon, boron, iron
Trace anions	Bromide, iodide, fluoride, sulphide, orthophosphate
Redox-sensitive species	NH_4, NO_2, NO_3
Naturally occurring isotopes	Tritium, ^{3}H, in water Stable oxygen, $^{18}O/^{16}O$, and hydrogen, $^{2}H/^{1}H$, isotopic composition of water Radiocarbon, ^{14}C, and stable carbon, $^{13}C/^{12}C$, in inorganic carbon Naturally occurring radioactive ^{36}Cl dissolved in groundwater
Reactive gases	Nitrogen, oxygen, carbon dioxide, hydrocarbons (C1-C5)
Inert gases	Neon, argon, krypton, xenon, helium, radon

Table A.10: Sources of Information on Chemical Analyses of Groundwater Samples

Borehole Number	Results contained in Nirex Report Number:	Summary Geochemistry Data Drawings in *Nirex Report SA/95/002* [COR/518]
1/1A	{106}	10180
2	{107}	10181
3	{108}	10182
4	{109}	10183
5	{371}	10184
7A	{307} {308}	10185
8A	{143}	10186
9A	{617}	
10A	{326}	10188
11A	{370}	10189
12A	{335}	10190
13A	{333}	10191
14A	{334}	10192
RCF1	{500}	10193
RCF2	{501}	10194
RCF3	{502}	10195
PRZ3	{609}	

Table A.11: Details Of Groundwater Pressure Monitoring System

Borehole No.	No. of Monitoring Zones			No. of Pumping Ports	No. of MOSDAX probes	Summary Drawing Numbers in *Nirex Report SA/95/002* [COR/518]
	Primary	Secondary	Total			
2	7	7	14	-	7	10111
4	9	21	30	-	9(4)	10112
5	-	-	3	-	3(1)	10113
7A	7	6	13	3	7	10114
7B	5	6	11	-	5	10115
8A	8	8	16	4	8	10116
8B	4	2	6	5	(2)	10117
10C	6	0	6	-	6	10118
11A	4	6	10	-	(2)	10119
12A	8	8	16	2	8	10120
13B	5	2	7	6	(2)	10121
14A	5	7	12	2	6	10122
RCF1	8	9	17	-	8	10123
RCF2	9	8	17	-	9	10124
RCF3	14	-	14	-	14(1)	10092
RCM1	10	10	20	-	17	10125
RCM2	10	12	22	4	17	10126
RCM3	7	7	14	-	13	10127
PRZ2	5	4	9	7	7	10128
PRZ3	6	6	12	-	6	10129
Holmrook 13	8	5	13	7	7	10130
Boonwood	6	0	6	5	6	10131
Total	154	134	288	45	163	.

Notes:

(1)	Alternative type of pressure transducer installed in Boreholes 5 and RCF 3
(2)	Installation data for MOSDAX probes after 24 July 1995.
(3)	12-packer string installed for Borehole RCF3 pump test
(4)	Configuration of MOSDAX probes changed on several occasions in response to requirements defined by testing programme.

Table A.12: Fracture Studies

Study	Description	Nirex Report Number
Remote sensing study	This comprised a study of aerial photographs and satellite imagery to identify linear features which could be indicative of the geological structure. Some direct observations were made of some of these features on the ground	{269}
Outcrop mapping - Phase 1	The initial phase of Borrowdale Volcanic Group fracture mapping was carried out in a 2 km by 1 km area in the Craghouse-Latterbarrow-Shepherd Crag area chosen as being the most extensive area of ourcrop closest to the PRZ. Outcrops were cleaned to provide better exposure	{BGS WA/94/04C}

	and sites ranging in area from approximately 25 m^2 to 5 m^2 were mapped. Within each of these areas all features more than 0.1 m long were traced and described. Geostatistical studies were carried out using the data collected.	
Outcrop mapping - Phase 2	A second phase of Borrowdale Volcanic Group outcrop mapping has been carried out in the Bleng Valley east of Gosforth. The study was designed to establish whether correlations could be established between the borehole sequences and the Borrowdale Volcanic Group outcrop immediately east of the Permo-Triassic cover and closest to the PRZ. The study also included investigation of the small scale structure and fracture mineralogy for comparison with the detailed characterisation available from the boreholes.	Not yet reported
Characterisation of fractures from borehole data	The fractures which occur within the boreholes have been characterised based upon visual logging, interpretation of the wireline imaging logs (Formation MicroImager and Acoustic Telescanner), and laboratory examination and testing (as part of core characterisation). One of the major outputs from this work has been the generation of a fully oriented dataset of the various types of fractures which occur in the boreholes.	{647, 644, 547, 637, 628, 649, 633, 543, 544, 545, 631, 546, 648, 540, 727}
Characterisation of fractures from wireline log data	Data derived from the wireline logging in the boreholes has been processed and interpreted to derive estimates of fracture aperture and extent.	as above
Structural domain studies	The data arising from the borehole characterisation of the fractures has been analysed to subdivide the rock mass into structural domains, that is, zones of rock having similar fracture characteristics and where these characteristics differ significantly from those of adjacent domains. Geostatistical correlation and fractal analysis have been undertaken to assist in extrapolation of data between boreholes.	{S/95/007, 520, CC180/N1161, S/95/005, BGS WA/95/47C}
Fracture mineralisation studies	Preliminary results obtained from the core characterisation studies {Nirex Report 520} indicated that several phases of fracture mineralisation could be recognised within the rocks at Sellafield. The mineralogical studies were therefore extended to identify the main characteristics of the fracture mineralisation and relate these to the regional patterns of mineralisation and, by dating the fracture filling minerals, to place them in the context of the history of fracturing and mineralisation events which have affected the region. These further studies have been subsequently extended to focus on the characterisation of the flowing features.	{SA/95/001, 520}
Flow Zone Characterisation	Characterisation of the flow zones has formed a major part of the fracture studies carried out in 1994. The data on location, orientation, mineralisation, aperture (from wireline log interpretation) and other characteristics of the identified flowing fractures have been integrated and analysed to interpret the characteristics of the flowing fractures, recognising that they represent a small proportion of the total fractures which occur in the rocks.	{S/95/006} {CC152/N1034}

Table A.13: Geotechnical Studies

Study	Description	Nirex Report Number
Measurements of geotechnical properties of the rocks	Determination of mechanical properties of rocks. This work has been carried out as part of the Core Characterisation Programme. See Table A.4 for list of tests carried out and Table A.5 for list of relevant Factual Reports and Summary Drawings.	See Table A.5
Measurements of in situ rock stresses.	(i) Hydrofracture stress measurements in Boreholes 2, 3, 5, 8A and 10A, including trial of Schlumberger Modular Formation Dynamics Tester. (ii) Overcoring stress measurements using Borre remote triaxial overcoring probe in Borehole 10B. (iii) Estimations of horizontal maximum and minimum stress directions from observations of borehole breakout in Boreholes 2, 3 and 4. The results of the hydrofracture stress measurements show a linear increase in stress with depth and there does not appear to be any evidence, so far, of different stress regimes in	Results reported in Appendix H to Factual Reports for individual boreholes. See Table A.3 for details of relevant report numbers.

	different formations or of major stress differences between boreholes. The horizontal stresses at a depth of 800 m are estimated to be minimum stress 18 MPa and maximum stress 29 MPa, a ratio of 1.8. The vertical stress is estimated to be about 21 MPa based on a rock density of 2.6 tonnes/m^3. Maximum stress orientations were determined to be in the range of 135° to 187°, average 165°. The results from the borehole breakout analysis are in the range 147° to 170°, consistent with the hydrofracture orientations. The results from the overcoring give maximum stress orientations in the range 119° to 156°, average 144°, again relatively consistent with the determinations using the other methods. The best preliminary estimate of the maximum horizontal stress direction is taken as 165°. This is consistent with published data for north west England and Western Europe.	
Characterisation of fractures by core logging and geotechnical mapping of rock outcrops.	Information on characteristics of fractures derived from core logging, outcrop mapping and interpretation of wireline logs.	See Table A.12 for further details of fracture studies and sources of factual data.
Modelling studies to examine the likely behaviour of rocks around underground excavations	Preliminary modelling work has been undertaken, primarily using the UDEC-BB code, to examine the likely rock support requirements for underground openings and the formation of excavation disturbed zones. This modelling has used data from boreholes and from outcrop mapping as input. There has been no opportunity to validate the output from these models in the absence of any underground openings within which direct measurements can be made.	{NGI Reports 931005-031 and 931005-51}

APPENDIX 2 - HYDROGEOLOGICAL BASELINE CONDITIONS

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Figure B.3.2: Stable Oxygen Isotope Results.

B.1. CONTEXT

B.1.1 Carrying out investigation and construction activities at the Site perturbs the groundwater pressures and can perturb the geochemical characteristics of the groundwater. The perturbations caused by construction of the RCF are likely to be more extensive than those caused so far by surface-based investigations. It is therefore important to have established both the groundwater pressures and the geochemical conditions before construction of the RCF commences. This is the concept of being able to define the 'baseline' conditions. This appendix to the evidence reviews the information obtained from the investigations so far and shows that baseline conditions have been established in terms of:

i. groundwater heads (Section B.2); and

ii. geochemical conditions (Section B.3)

B.2. GROUNDWATER HEADS

Availability of Data

B.2.1 The monitoring network comprises instrumentation installed in 22 boreholes and incorporating the provision to record groundwater pressures in 288 individual sections of the boreholes. Currently, 163 of these sections are fitted with automatic recording equipment (Table A.11, Appendix 1). The groundwater pressure monitoring data are presented for each borehole in which instrumentation is installed in Drawing Nos. 10111 to 10131 in *Nirex Report SA/95/002* [COR/518].

Performance of the Monitoring System

B.2.2 In order to be able to use the pattern of groundwater pressure changes caused by construction of the RCF to obtain an understanding of the hydrogeological properties of the site it is necessary to be able to distinguish construction effects from those which are due to other effects, whether natural or artificially induced. McEwen et al in their report to the Department of the Environment *(Review of Data Requirements for Groundwater Flow and Solute Transport Modelling and the Ability of Site Investigation Methods to Meet these Requirements. McEwen TJ, Chapman NA and Robinson PC, DOE/ HMIP/RR/90.095, DOE 1990.* [GOV/610]) (Section 3.6.1, page 116) emphasise this as:

> *"By drilling, testing and monitoring boreholes in the area of the proposed shaft for a sufficiently extensive period before any construction commences, the changes due to the shaft construction should be adequately quantified."*

B.2.3 The Radioactive Waste Management Advisory Committee (RWMAC) in their *Response by the RWMAC: UK Nirex Ltds Consultative Document on a Rock Characterisation Facility. HMSO, February 1993.* [GOV/408], stated (paragraph 19, page 7) that a period of eighteen months to two years of monitoring prior to the commencement of shaft sinking could be regarded as normal practice.

B.2.4 When monitoring instrumentation is installed in the ground, the installation process (including drilling the borehole) may itself perturb the groundwater system. Thus when monitoring commences the groundwater pressure is observed to change with time until the perturbation caused by the installation process has been dissipated. In general terms, this dissipation occurs more rapidly the higher the hydraulic conductivity of the rock. This is the 'settle-down' period. Furthermore, in certain environments the groundwater pressures can vary significantly due to natural processes, such as seasonal variations in recharge, or variations in groundwater abstraction. In these circumstances it may be necessary to monitor groundwater pressures for long periods of time (months or years) in order to define the background variations in sufficient detail to allow the perturbations resulting from testing and/or construction to be distinguished from the background variations.

B.2.5 Initial trials with the instrumentation {S/94/006} evaluated the use of manual monitoring (in which a probe is lowered down the borehole, a measurement made and then the probe removed) and automatic monitoring (in which a transducer is installed in each section of the monitoring borehole and the pressure measured via a cable connection to a computer located at the surface without the need to remove the probe). These trials indicated that manual monitoring tended to produce occasional anomalous readings. These were investigated and found to result largely from the disturbance of the pressures in the system

caused by the process of inserting and removing the monitoring probe. The automatic monitoring, since it avoided the need to introduce and remove a probe into the borehole each time a measurement was to be taken, did not cause the disturbance noted with the manual monitoring. In addition, the automatic system allowed for more frequent measurements, with each section in the borehole being monitored at intervals of between 2 minutes and 30 minutes.

B.2.6 Nirex has taken the decision progressively to install automatic recording in all the boreholes. So far, all except three boreholes have been equipped with automatic equipment. These remaining three boreholes will be converted to automatic recording as soon as the probes become available from the manufacturers.

Results

B.2.7 Settle-down effects have been observed in several of the boreholes, notably Boreholes 2, 4, 5, 8A, 11A, RCF2 and RCM3. The longest settle-down periods were observed in Borehole 8A where the measured heads continued to fall for around 3 months and in Borehole 11 where heads rose for a period of approximately 8 months following installation of the instrumentation. These latter changes were entirely recorded during periods when manual monitoring was being employed and could in part be a result of the perturbations caused to the groundwater system by manual monitoring itself.

B.2.8 Following settle-down, the horizontal lines on the monitoring plots, indicating a constant head with time, are indicative of baseline having been established. These baseline conditions are shown as having been perturbed by variations in head with time, associated with drilling or testing.

B.2.9 Figure B.2.1 is an example of monitoring data to illustrate the establishment of baseline. This diagram shows the data from the Boonwood Borehole for the period from June 1994 to May 1995. Baseline conditions were established at the start of the record in May 1994 as shown by all the monitoring zones recording a constant head at 80 metres aOD. In mid-June 1994 the head data begins to show irregular fluctuation due to various drilling and testing activities in adjacent boreholes. There is a break in the records from late November 1994 to mid-January 1995. After resumption of monitoring, the three zones labelled P1, P2 and P3 are back at baseline at +80 metres OD whereas the zones P4, P5 and P6 are being perturbed by pump testing in Borehole RCF3. These latter sections subsequently recover and are back at baseline by the end of the record in early May 1995. In the meantime zones P1, P2 and P3 have been perturbed by a second phase of pump testing and then recover to 80 metres aOD in May.

B.2.10 Those boreholes which have not been influenced by drilling and testing are shown by the monitoring data to maintain constant pressures in the monitored zones or to display systematic variations. The variations identified from the monitoring data at the site are described below.

<u>Seasonal variations and longer terms trends</u>

B.2.11 Long-term fluctuations in groundwater heads have only been identified in datasets from shallow Sherwood Sandstone Group boreholes which have been monitored for over 20 years. A mean increase in heads of 0.7 metres during the period 1974 to 1981 was followed by a decrease in heads of a similar magnitude during the period 1981 to 1994;

B.2.12 Seasonal variations in groundwater heads in the Sherwood Sandstone Group with amplitudes of 0.4 to 4 metres reaching highs in the spring and lows in the autumn are identified in the monitoring network and shallow open borehole datasets. No clear seasonal variations are identified in formations below the Sherwood Sandstone Group with the exception of fluctuations in the upper parts of the Borrowdale Volcanic Group in Boreholes 8A/8B;

<u>Barometric fluctuations</u>

B.2.13 Fluctuations in groundwater heads, related to variation in atmospheric pressure are identified in the monitoring network datasets and shallow open borehole records. The magnitude of these fluctuation ranges from 20 to 65 per cent of the barometric pressure changes, or approximately 0.1 to 0.3 metres head; and

Short-term cyclic fluctuations

B.2.14 Semi-diurnal and diurnal fluctuations in groundwater heads are identified in all shallow open sandstone boreholes fitted with transducers and data loggers and in all the monitoring network datasets. The 12 to 13 hour period fluctuations have amplitudes in the range of 0.005 to 0.04 metres head, while the 25 to 26 hour period fluctuation have amplitudes in the range of 0.002 to 0.02 metres head. These amplitude variations may be related to the hydraulic conductivity of the monitoring zone but this has yet to be fully analysed.

B.2.15 Various groupings of monitoring zones in Borehole 4 are also observed to have semi-diurnal fluctuations which are out of phase with other groups of zones. The cause of these phase shifts is not yet understood but one shift appears to coincide with the depth of the head increase around 800 metres bOD.

Conclusions

B.2.16 The monitoring data thus shows:

i. Settle-down periods which are generally very short, but which, in a limited number of cases, can last for several months;

ii. Baseline conditions which are recognisable in all boreholes as shown by constant head with time or systematic seasonal variations; and

iii. Perturbations caused by drilling and testing which are clearly distinguishable from baseline conditions.

B.2.17 Assuming that planning permission is granted for construction of the RCF in June 1996, construction of the shafts will commence in late 1996. A further 18 months of monitoring (July 1995 to December 1996) will thus be available prior to perturbation of the groundwater system by construction.

B.3. GEOCHEMICAL CONDITIONS

Context

B.3.1 The geochemical characteristics of the groundwater are required as an input to developing an understanding of the geology and hydrogeology of the Site. Geochemical characterisation aims to establish the pattern of chemical variations in the groundwater and interpret this to provide evidence of past and current mixing processes and of chemical reactions between the groundwater and the rocks within which they occur {S/95/008}. This appendix to my evidence reviews the information currently available on the geochemical characteristics of the Site.

Spatial Coverage

B.3.2 The number of groundwater samples available for collection is controlled by the availability of suitable sampling locations. In the Nirex Deep Boreholes groundwater can only be collected in sufficient quantity, for the necessary wide range of analyses, from the flow zones.

B.3.3 Currently available information from the Nirex Deep Boreholes now comprises 166 groundwater samples from Boreholes 1/1A, 2, 3, 4, 5, 7A/B, 8A, 10A, 11A, 12A, 13A, 14A, RCF1, RCF2, RCF3, RCM1, RCM2 and PRZ3. This number of samples compares with only 66 samples which were available in 1993 and formed the basis of the interpretation of geochemical conditions published in *Nirex Report 524* [COR/517] (Section 3, Volume 3).

B.3.4 In addition to the data available from the Nirex Deep Boreholes, data are also available from water samples obtained from the following sources {S/95/008}:

i. rivers and groundwater discharge points such as onshore and shoreline springs, and pumped and flowing boreholes {499}. Data available prior to the Nirex investigation extends back to 1976 and has been used to supplement the data collected by Nirex;

ii. rainwater samples; and

iii. water samples obtained from lake sediments from Derwent Water and Wast Water.

B.3.5 In the Nirex Deep Boreholes, the number of flow zones limits the number of groundwater samples that can be obtained for chemical analysis (See Section B.3.4 above). Information to assist in the interpretation of groundwater chemistry between these sampled locations has been obtained from two sources, namely:

i. geophysical wireline logging data : a suite of electrical resistivity logs was run in each of the boreholes. The data have been used to determine the position of significant changes in groundwater salinity and provide in-fill information between the widely spaced groundwater samples; and

ii. core pore-fluid data: estimates of the chemical composition of pore-fluids in core from some of the Nirex Deep Boreholes have been derived from chemical analysis of pore-water centrifuged from core material or from aqueous leaching of residual pore-water solutes from core material. Chloride and bromide values from pore-water show general agreement with those derived from groundwater samples. As with the wireline log data, this core pore-water data has been used to provide information between the widely spaced groundwater samples.

B.3.6 Some gaps in the spatial coverage of data have been recognised outside the PRZ. These gaps are being filled by additional drilling from the Borehole 9 site and Boreholes 15 to 18 (See Table 6.3 (a)).

B.3.7 The latest detailed review of the geochemistry published by Nirex {S/95/008} concludes that:

i. The newly available data are broadly consistent with the overall interpretation published in *Nirex Report 524* in 1993 [COR/517]. Thus, as increasing amounts of data are obtained, the interpretation of the geochemistry of the site remains essentially unchanged; and

ii. All groundwater compositions observed at the site to date can be attributed to mixing between four identified components; a deep basinal brine in the west, a deep saline basement water in the east; and two types of fresh water, a shallow water of recent origin and an older deep type {S/95/008}.

B.3.8 Examples of the way in which new data are confirming previous data are presented in Figures B.3.1 and B.3.2. These diagrams show the data presented in *Nirex Report 524* in 1993 [COR/517] and compares this to data presented in Nirex Report S/95/008 in mid 1995 {S/95/008}. The two examples are for chloride/bromide ratios (Figure B.3.1) and oxygen isotope data (Figure B.3.2), both plotted against chloride concentrations. The new data are consistent with the previous data, but, by filling in gaps in the data, are for example indicating a continuous sequence of mixing of groundwater types rather than indicating the presence of separate discrete compositions of water. The chloride/bromide data are important because they help to indicate the presence of separate sources for the salinity in the groundwater. The oxygen isotope data are important because of the information they provide on the age of the water (See Paragraph 6.65 of Main Proof of Evidence).

Range of Chemical Analyses

B.3.9 The range of analyses carried out on groundwater samples are listed in Table A.9 in Appendix 1.

B.3.10 This list has been reviewed by specialist geochemists working in the Nirex programme, by the Nirex Review Panel and by the Royal Society Study Group and found to be sufficiently extensive in terms of the range of analysis in comparison with the corresponding radioactive waste disposal programme in Sweden, Switzerland and Canada.

Reliability of Chemical Data

B.3.11 All samples are collected, handled, preserved and stored using procedures to minimise or eliminate sample contamination prior to analysis. All samples from the Nirex Deep Boreholes are nevertheless variably contaminated with drilling fluid and the analytical results are corrected to estimate true groundwater compositions (See Sections A.4.4 - A.4.6 in Appendix 1).

B.3.12 All analytical methods adopted on the investigation are based on industry standard methods, modified as necessary to suit the particular compositions of the groundwater at the Site to ensure that the quality of the analysis is readily demonstrable. The accuracy of most of the methods has been demonstrated against international standards, within recognised inter-laboratory analytical comparison schemes or against specially prepared internal standards. Ion balance calculations and comparisons of measured and calculated total dissolved solids data are used to demonstrate the accuracy of the major ion analyses. The uncertainties associated with all analyses are monitored through replicate analyses of samples, analyses of duplicate samples and repeated analysis of independent standards.

Conclusions

B.3.13 It is concluded that the chemical characteristics of the groundwater conditions at present are sufficiently well defined and understood such that we can monitor the perturbations of the system by construction of the RCF, and interpret the results to provide a better understanding of the groundwater system.

B.3.14 This conclusion are based on the following:

i. the number of samples analysed to date and their locations are sufficient to establish the distribution of the different types of groundwaters;

ii. the range of chemical analyses carried out are sufficient to establish the significant characteristics of the groundwaters; and

iii. the chemical data has a high level of reliability that provides confidence in the results arising from the investigations. This confidence arises from the standards and procedures adopted for the collection and analysis of samples and processing of the results to remove the effects of drilling fluid contamination.

FIGUR B.2.1: EXAMPLE OF MONITORING DATA FROM BOONWOOD BOREHOLE
(Click on image to see in full size)

Figure B.2.1: Example of monitoring data.

FIGURE B.3.1: BROMIDE/CHLORIDE RATIOS
(Click on image to see in full size)

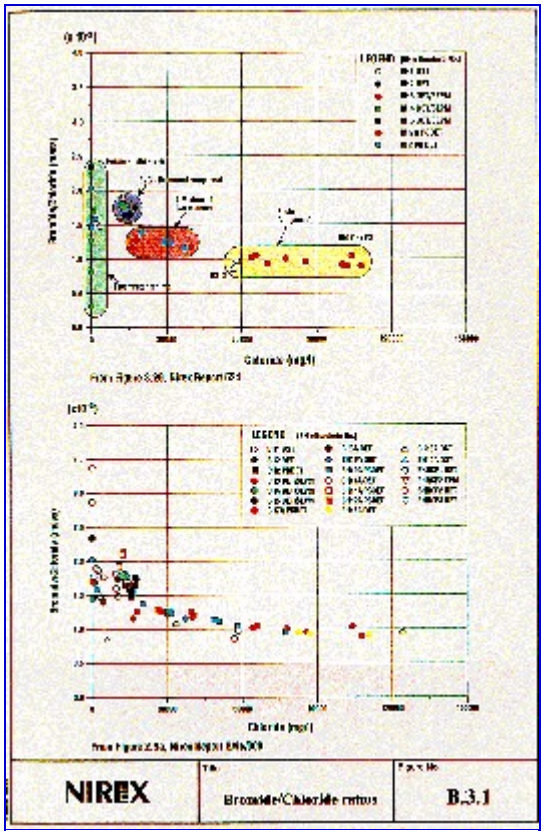
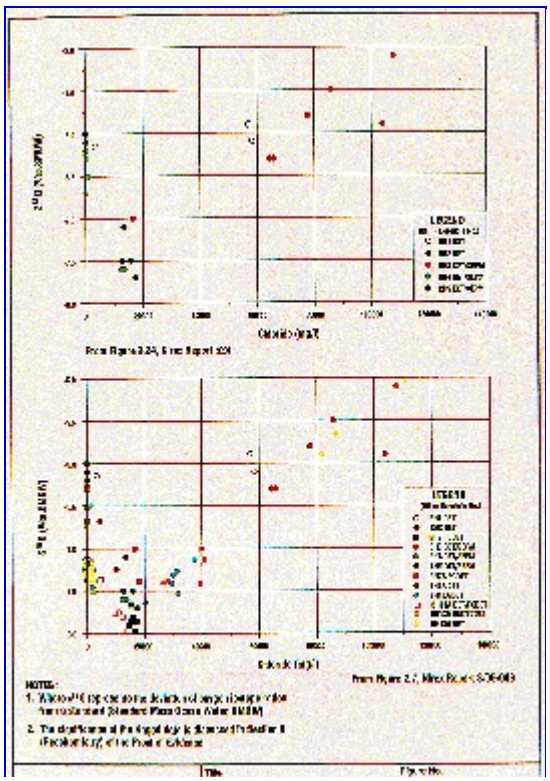


FIGURE B.3.2: STABLE OXYGEN ISOTOPE RESULTS
(Click on image to see in full size)



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NIREX

PE/NRX/14

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LPA Ref: 4/94/9011
DOE Ref: APP/HO900/A/94/247019

UNITED KINGDOM NIREX LIMITED

Rock Characterisation Facility

Longlands Farm, Gosforth, Cumbria

PROOF OF EVIDENCE

OF

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TABLE 3.1: DOCUMENT STRUCTURE

Type of Report	Publication status	1992	1993		1995
Proof of Evidence	PUBLISHED	.	.		Proof of Evidence [PE/NRX/14]
Executive Summary Report	PUBLISHED	.	Nirex Report 525 [COR/505]		.
Reports Summarising Results (Inquiry Documents)	PUBLISHED	.	Nirex Report 524 [COR/517]		Nirex Report SA/95/002 [COR/518]
Detailed Nirex Report (Figures in brackets indicate Nirex Report Numbers)	PUBLISHED	{263-272}	{341}	{346}	{SA/94/006 to 008}
			{515-521}		{S/95/005 to 008}
Factual Report	NOT PUBLISHED - AVAILABLE FOR REFERENCE	119 Reports and approximately 1600 appendices See Tables A.1 to A.3, A.5, A.8, A.10, and A.12 in Appendix 1 and Nirex Report SA/95/002 for details			

TABLE 6.1: MINERALISATION EPISODES

Mineralisation Episode	Mineralisation Type	Description
ME1	Silicate	Mineralisation episodes ME1 to ME3 only affect the Borrowdale Volcanic Group rocks. They are therefore considered to be older than the oldest sedimentary cover rocks of Lower Carboniferous age, ie more than 350 million years old.
ME2	Silicate (and carbonate)	The ME2 quartz-dominated early mineralisation fractures are confined to the Borrowdale Volcanic Group. There appears to be a strong bond between fracture mineralisation and the wallrock such that veins do not appear to have been reactivated. These early veins are commonly cross-cut rather than having been exploited by the later carbonate- or sulphate-dominated mineralisation.
ME3	Sulphide (and silicate)	Only affects BVG rocks.
ME4	Sulphate	ME4 affects both basement and cover rocks and is attributed to fracture movement resulting from early to middle Triassic subsidence and growth fault development.
ME5	Silicate	ME5 and ME6 represent complex stages of progressive deep burial, fracture movement and mineralisation.
ME6	Carbonate and sulphate, with hematite	The ME6 mineralisation has several phases and includes some carbonate mineralisation. There is some correlation between this period of mineralisation and the flowing features in the BVG. The ME6 fracturing and mineralisation had ceased in the Sellafield area by the late Triassic (more than 214 million years ago).
ME7	Silicate and oxide	ME7 fracture mineralisation is dominated by illitic clays either as late fracture infills, or as illite precipitated within fault gorges. K-Ar dating indicates that this occurred in relation to fracture movements over a protracted period from 214 million years (late Triassic) to at least 60 million years (Tertiary). The youngest ME7 age (about 60 million years) in the BVG is at least well-constrained and is not associated with fracture movement. It may reflect mineralisation due to hydrothermal fluid flux and/or thermal pulse associated with Tertiary igneous activity. Similar mineralisation has been reported both in the East Irish Sea Basin and across northern England, suggesting that this was a widespread regional thermal event.
ME8	Oxide	ME8 is only found in the upper parts of the St Bees Sandstone and Calder Sandstone and increases in significance towards the surface. It is believed to be caused by oxidative dissolution attributable to modern groundwater or possibly to deep Tertiary weathering. There is no evidence of fracture movement during this stage of mineralisation.
ME9	Carbonate	Studies of the mineralisation associated with the identified flowing features has identified a ninth characteristic mineralisation episode ME9. This is characterised by the presence of 'Late Calcite' crystals in the fractures. Late Calcite is characterised by translucent or pale brown, well shaped crystals. They range in size reflecting the size of the aperture into which they grew. The good crystal form indicates that the fractures were open and permeable to groundwater in their natural state. The Late Calcite is of the same age as the ME7 mineralisation or is younger. The delicate crystals have not been disrupted or fragmented by fault activity or fracture reactivation. The presence of Late Calcite is probably the best means of identifying potentially flowing features both in the area of core where groundwater flow is known to occur, and in areas for which there is otherwise no evidence for flow. Further work is in progress to characterise this mineralisation further.

TABLE 6.2: GEOCHEMICAL INDICATORS OF GROUNDWATER RESIDENCE TIMES {S/95/008}

Technique	Description
Stable oxygen and hydrogen isotopes	The stable oxygen and hydrogen isotopes indicate a distinction between groundwaters in different parts of the site. The waters obtained from the Borrowdale Volcanic Group at depth in the PRZ are different to the other deep boreholes and

	present day rainfall. The water does, however, have a signature which indicates it is derived from meteoric recharge. This is interpreted as indicative of recharge under a colder climate. The last glacial period ended some 10,000 years ago.
Noble Gas Analyses to determine recharge temperatures	Recharge temperatures have been estimated from the analysis of noble gas concentrations. Again the deep PRZ waters are distinctly different from other groundwaters. This supports the interpretation of recharge in a glacial period. The stable oxygen and hydrogen isotope data, together with the noble gas data could also be interpreted as indicating recharge at higher altitudes.
Tritium	After having removed the effects of contamination from drilling fluid, the tritium contents of the deep PRZ waters are indistinguishable from zero, indicating absence of young waters at depth.
Carbon-14	Carbon-14 analyses are subject to significant uncertainty due to the effects of the drilling fluid, air contamination and degassing of CO_2 during sampling. A few samples with contamination levels of around 1% are suggesting that the deep groundwater does not contain modern carbon. If this is so, then the groundwater in the deep PRZ is in excess of 30,000 years old. Further samples with low levels of contamination are being analysed.
Chlorine-36	Chlorine-36 is a useful indicator of solute residence times because contamination effects are not significant due to the high salinity of the groundwater. The ratio of chlorine-36 to chlorine of the saline waters from the PRZ in Borehole 2 is consistent at around 21 to 27 x 10^{-15}. This is what would be expected for a water in equilibrium with in situ neutron flux in the Borrowdale Volcanic Group rocks. To reach this equilibrium requires a residence time of around five half-lives which implies that the chloride in the groundwaters of the PRZ have been in a host rock with a similar flux for at least 1.5 million years.
Helium-4	Helium-4 abundances have been determined for groundwater from Boreholes 2 and 4 in the PRZ. Subject to a range of uncertainties, the results suggest a residence time similar to those indicated by the chlorine-36 studies.

TABLE 6.3: PLANNED PROGRAMME OF FURTHER SURFACE-BASED INVESTIGATIONS

(a) GROUNDWATER FLOW AND RADIONUCLIDE TRANSPORT			
Activity	**Description**	**Status**	**Relationship to RCF**
Boreholes 15-18	Series of up to four boreholes in the area to the north-west and west of the PRZ to obtain a better understanding of the saline interface zone and its influence on groundwater flow.	Planning application for Boreholes 15 and 16 submitted on 31 May 1995.	Boreholes located outside PRZ, accordingly information cannot be obtained from RCF.
Drilling from Borehole 9 Site	Further drilling at the Borehole 9 site, as required, to gain a better understanding of groundwater conditions where groundwater recharge is believed to be occurring.	Planning permission received for additional boreholes from Borehole 9 site.	Boreholes located outside PRZ, accordingly information cannot be obtained from RCF.
Drilling into Seascale Fault Zone	Up to two inclined boreholes into the Seascale Fault Zone to the south of the PRZ to obtain information on the hydrogeological significance of this geological structure.	Planning permission received for two inclined boreholes from the Borehole 11 site.	Boreholes located outside PRZ, accordingly information cannot be obtained from RCF.
Borehole PRZ1	Inclined borehole in the PRZ to investigate the influence of the geological structure on hydrogeological conditions.	Drilling commenced and temporarily halted during progress of pump test.	To be completed before commencement of RCF.
Continuation of Hydrogeological Monitoring	Continuation of monitoring of site conditions utilising instrumentation already installed in deep boreholes, spring and river gauging and meteorological monitoring.	Ongoing.	integral part of RCF science programme to monitor response of groundwater system to excavation of RCF.
Laboratory testing	Analytical work on samples of rock and groundwater is continuing. Numerous samples from the investigations are still being analysed. Further samples are being collected and will require analysis.	Ongoing.	Currently proceeding independently of RCF. Samples from the RCF, when available, will be included in the programme of testing.
(b) NATURAL AND INDUCED CHANGES TO THE GEOLOGICAL BARRIER			
Activity	**Description**	**Status**	**Relationship to RCF**
Monitoring	Earthquake and acoustic emission monitoring.	Ongoing.	Integral part of science programme to permit continued monitoring of earthquakes, acoustic responses of rock to excavation of RCF and to permit comparison of these effects with any observed responses of the groundwater system.
Quarternary Studies	Investigation of Quarternary deposits using trial pits, boreholes and geophysical surveys.	Ongoing.	Integral part of the overall science programme
(c) DESIGN AND CONSTRUCTION OF THE REPOSITORY			
Activity	**Description**	**Status**	**Relationship to RCF**
3-D Seismic reflection surveys	Interpretation of the trial 3-D seismic survey is proceeding. If this technique is shown to permit enhancement of the existing geological model of the PRZ an evaluation will be made of the potential value of extending the survey area to provide additional	Ongoing.	Potentially part of the RCF science programme to enhance the existing geological model which is to be validated in the RCF.

	information on the geological structure and rock properties at depth in a wider area.		
Borehole RCF4	Borehole on centreline of RCF North Shaft for construction planning.	Planning permission received. Borehole due to be drilled late 1995.	Needed prior to commencement of construction of the RCF North Shaft. Drilling deferred pending completion of pump test.
Geophysical surveys	Seismic, electro-magnetic and other techniques are being used to assist in the further interpretation of site conditions.	Ongoing.	Independent of the RCF.

FIGURE 4.1: SELLAFIELD GEOLOGICAL INVESTIGATIONS: AREA DEFINED

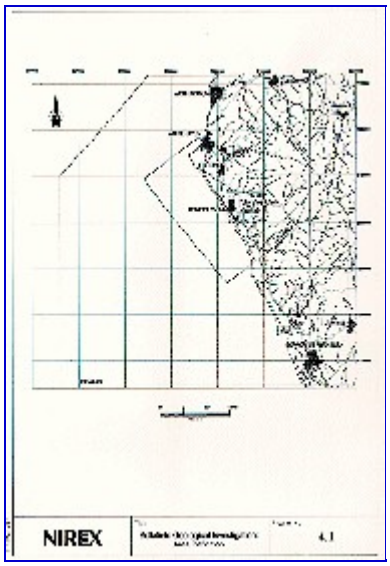


FIGURE 4.2: LOCATION OF NIREX DEEP BOREHOLES WITHIN THE SELLAFIELD SITE AREA

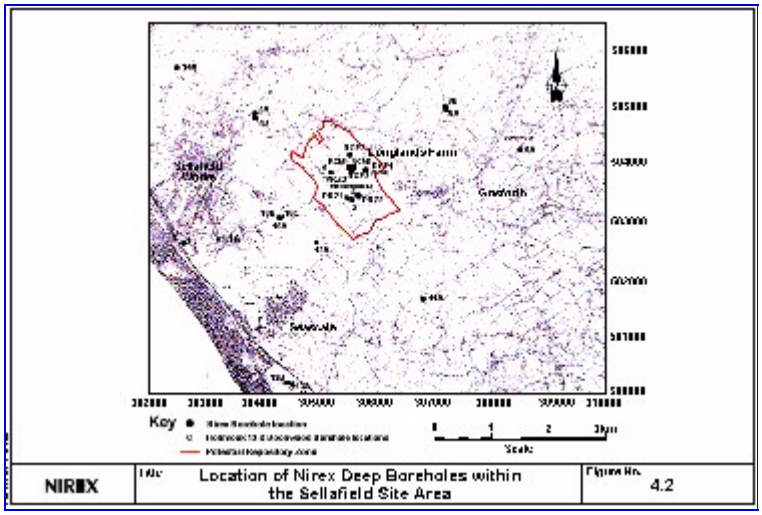


FIGURE 4.3: LOCATION OF NIREX DEEP BOREHOLES WITHIN THE SELLAFIELD PRZ AREA

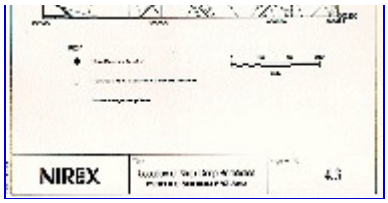


FIGURE 5.1: GEOLOGICAL SEQUENCE IN THE SELLAFIELD REGION (Ages after a 'Geologic Time Scale' by Harland et al., Cambridge University Press, 1990)

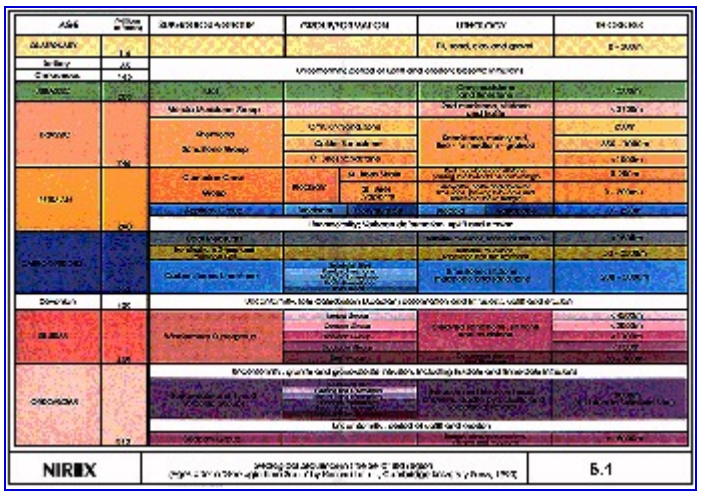


FIGURE 5.2: CROSS-SECTION THROUGH POTENTIAL REPOSITORY ZONE

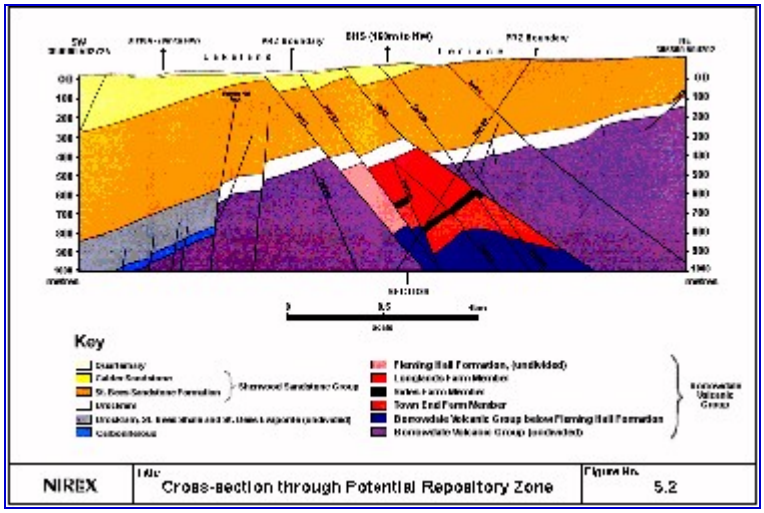


FIGURE 5.3: THREE-DIMENSIONAL REPRESENTATION OF TOP BASEMENT IN THE SELLAFIELD 'DISTRICT' AREA

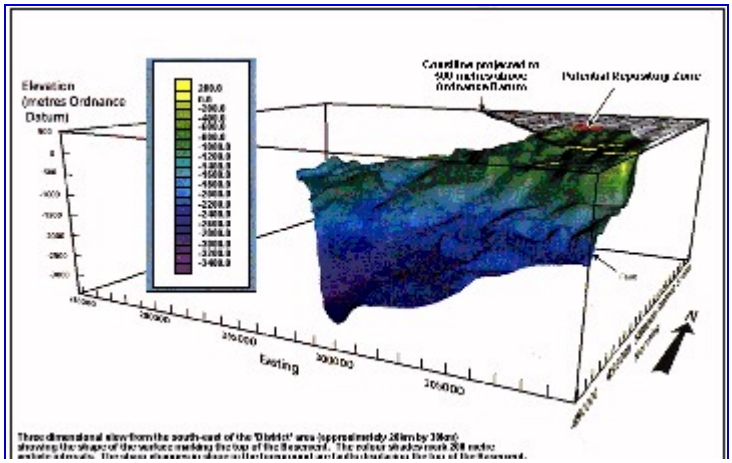


FIGURE 5.4: THREE-DIMENSIONAL GEOLOGICAL MODEL OF THE RCF AREA

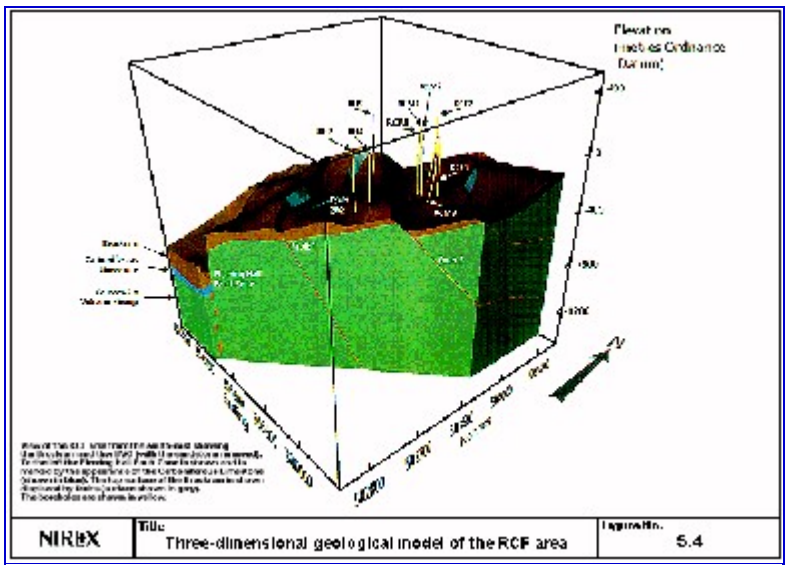


FIGURE 5.5: GEOLOGICAL STRUCTURE OF THE PROPOSED AREA OF THE ROCK CHARACTERISATION FACILITY

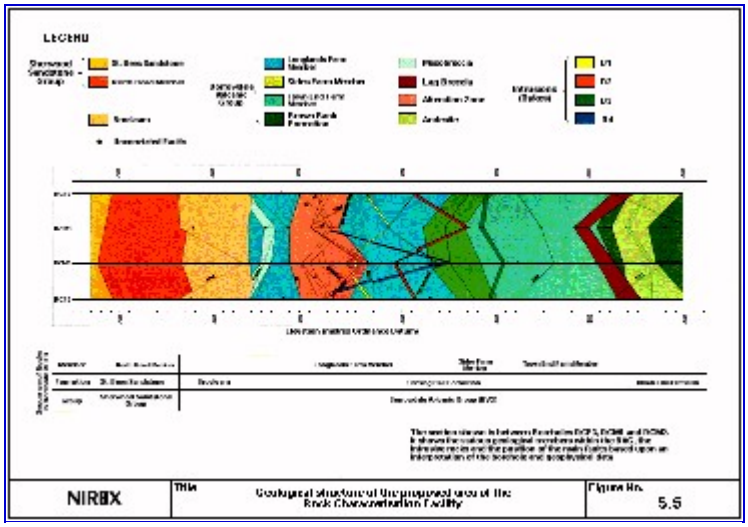


FIGURE 6.1 : SUMMARY OF HYDRAULIC CONDUCTIVITY VALUES

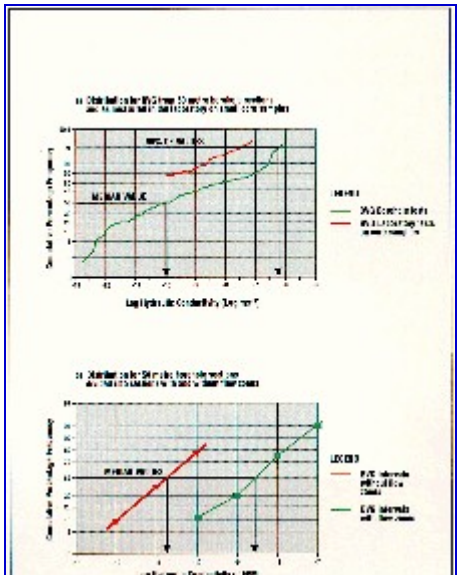


FIGURE 6.2: HYDRAULIC CONDUCTIVITY VALUES FOR SHORT INTERVAL HYDRAULIC TESTING

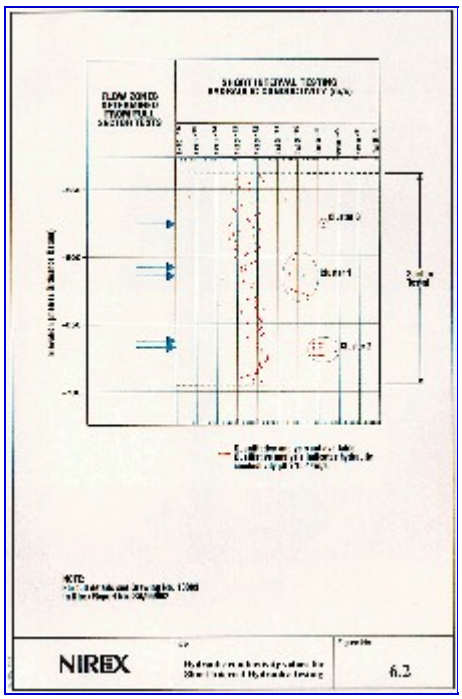


FIGURE 6.3: FLOW ZONES: DISTRIBUTION OF INFILL MATERIAL

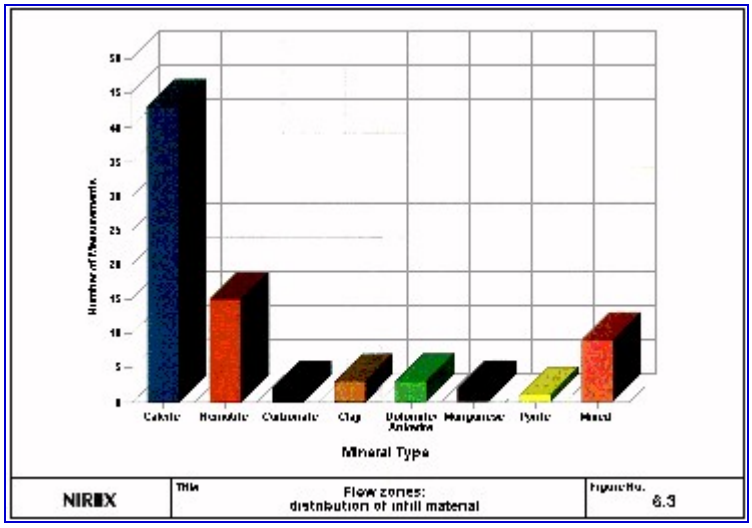


FIGURE 6.4: FLOW ZONES: DISTRIBUTION OF MINERALISATION EPISODE

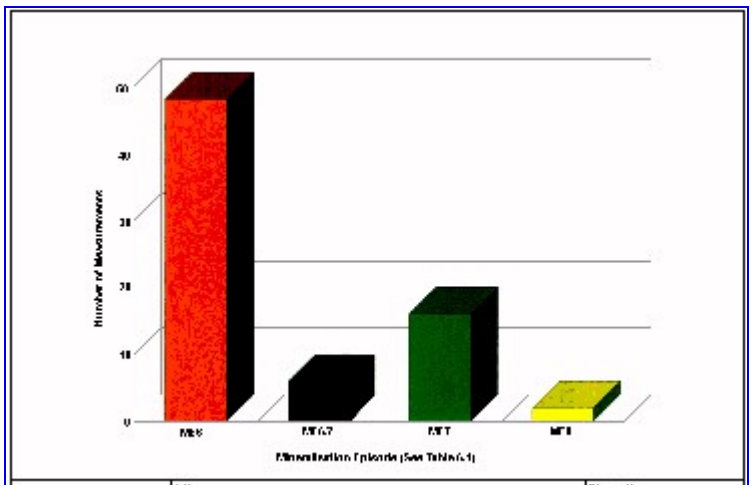


FIGURE 6.5: FRACTURE NETWORK TESTING: OBSERVED RESPONSE AND FLOW ZONES

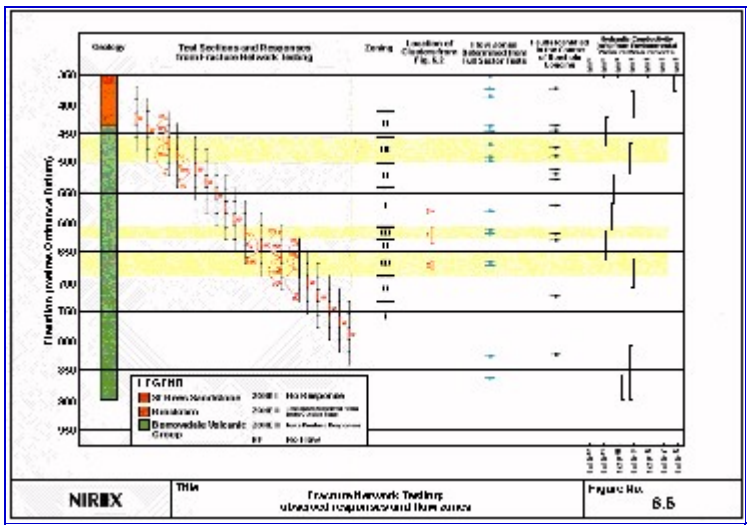


FIGURE 6.6: RESULTS OF CROSS-HOLE HYDRAULIC TESTING IN BOREHOLES 2 AND 4

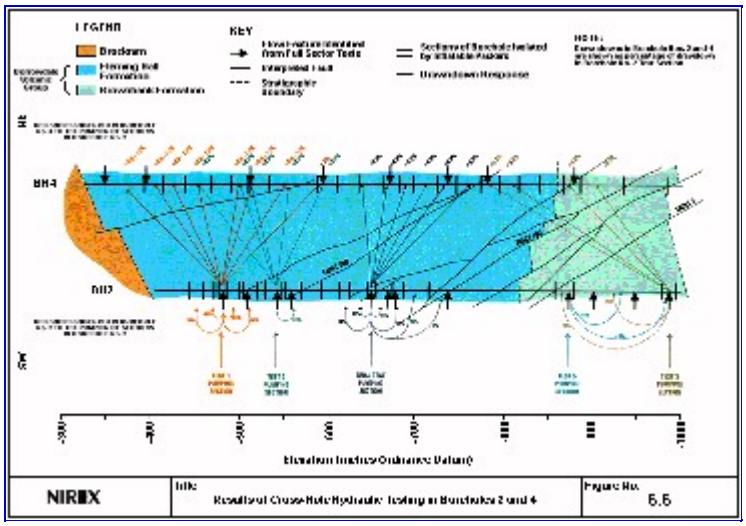


FIGURE 6.7: RESULTS OF BOREHOLE RCF3 PUMP TEST

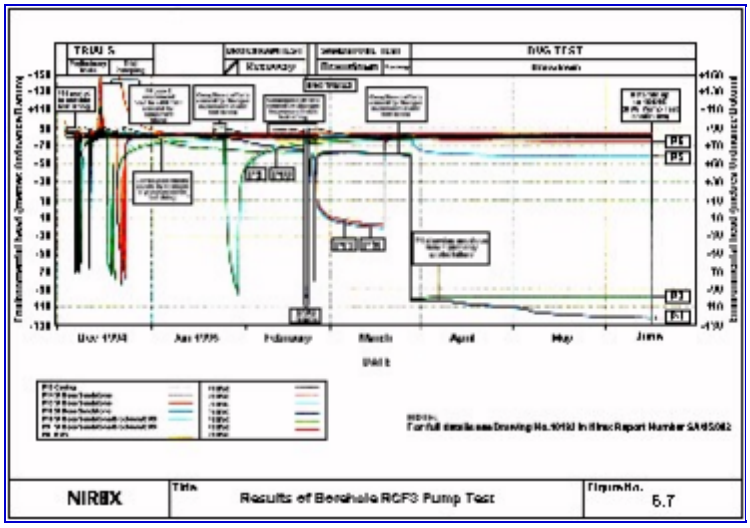
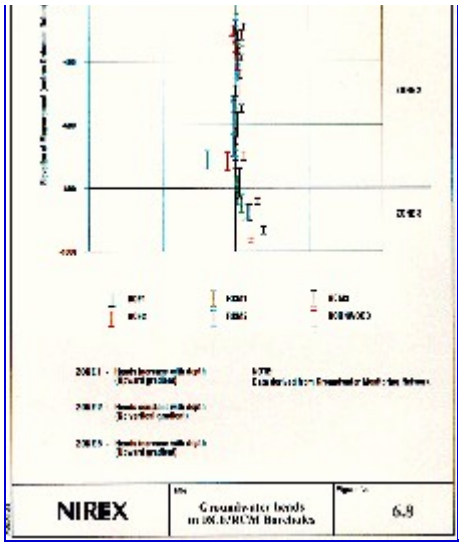


FIGURE 6.8: GROUNDWATER HEADS IN RCF/RCM BOREHOLES



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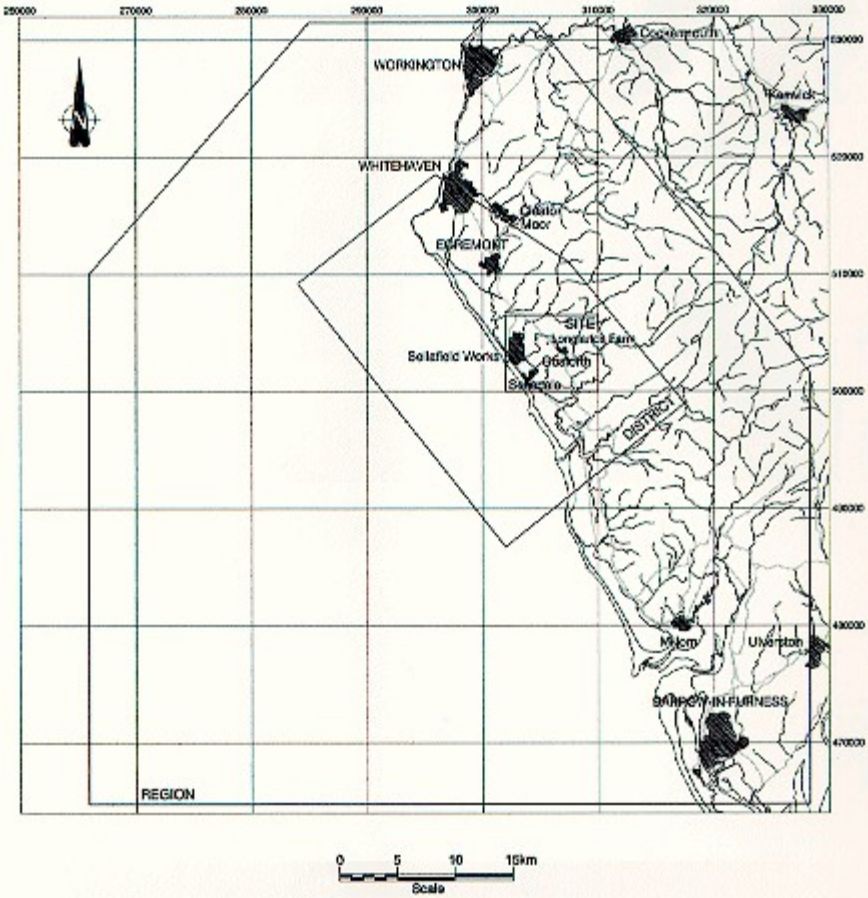
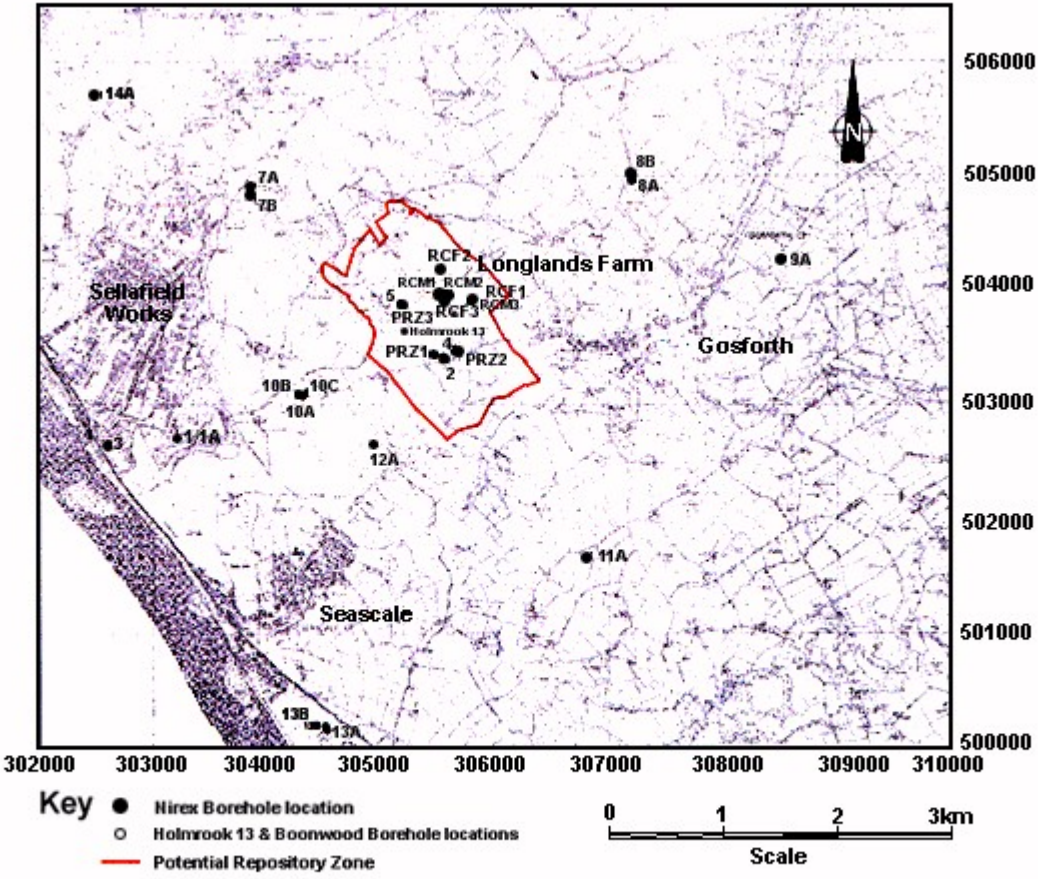
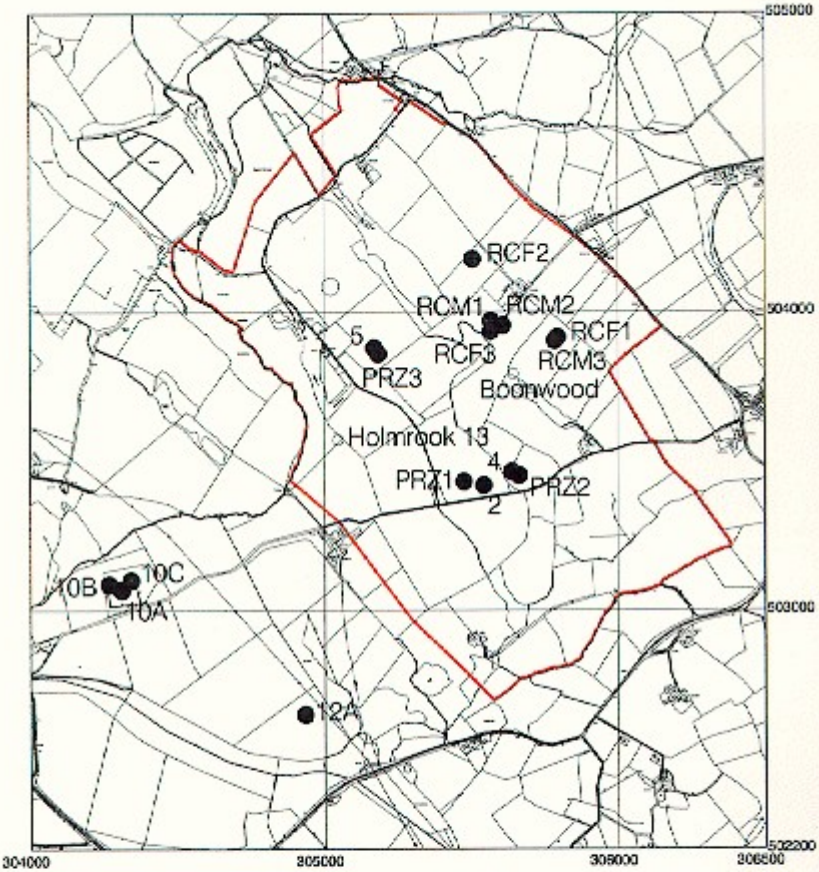


NIREX	Title Sellafield Geological Investigation: Area Definition	Figure No. 4.1



NIREX	Title	Location of Nirex Deep Boreholes within the Sellafield Site Area	Figure No. 4.2



KEY

Nirex Borehole location

Holmrook 13 & Boonwood Borehole locations

Potential Repository Zone

0 250 500 750m

Scale

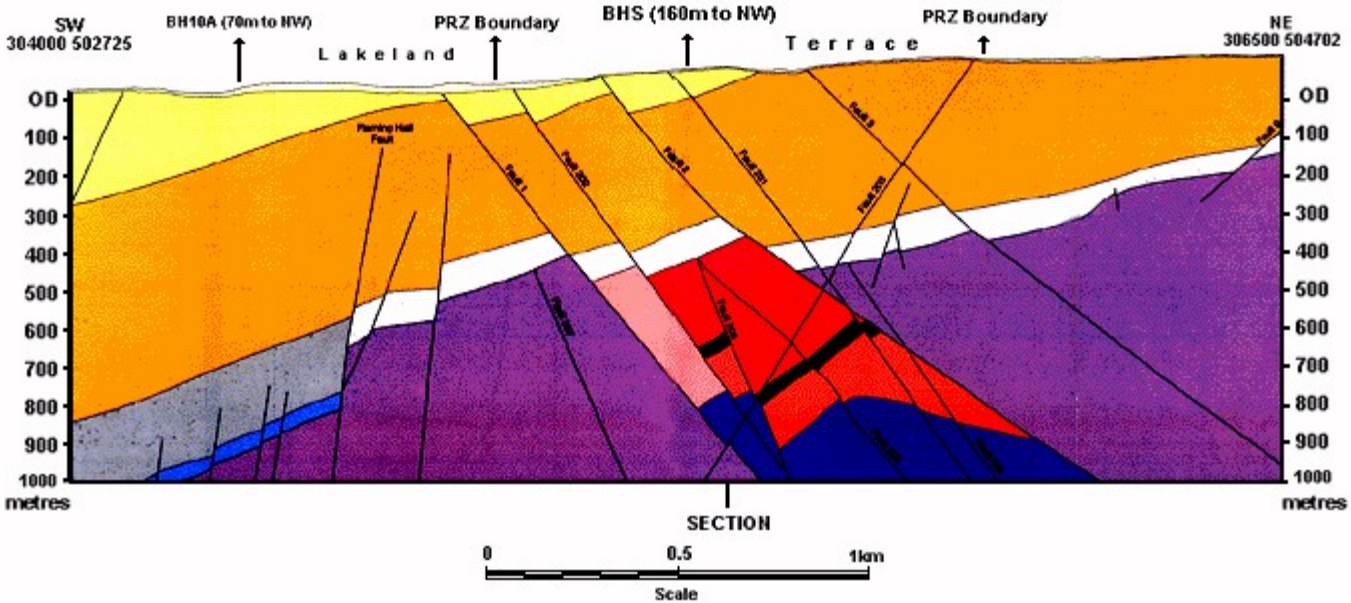
NIREX	Title Location of Nirex Deep Boreholes within the Sellafield PRZ Area	Figure No. 4.3

AGE	(Millions of Years)	SUPERGROUP/GROUP	GROUP/FORMATION		LITHOLOGY		THICKNESS
QUATERNARY	1.6				Till, sand, clay and gravel		0 - 300m
Tertiary	65	Unconformity; period of uplift and erosion; basaltic intrusions					
Cretaceous	146						
JURASSIC	208	Lias			Grey mudstone and limestone		<500m
TRIASSIC	246	Mercia Mudstone Group			Red mudstone, siltstone and halite		<3700m
		Sherwood Sandstone Group	Ormskirk Sandstone		Sandstone, mainly red, fine - to medium - grained		250m
			Calder Sandstone				650 - 1000m
			St. Bees Sandstone				<1000m
PERMIAN	290	Cumbrian Coast Group	Brockram	St. Bees Shale	Red mudstone and siltstone, passing into breccia at basin margin		0-200m
				St. Bees Evaporite	Anhydrite, halite and dolomitic limestone, passing into shale and breccia at basin margin		0 - 200m+
		Appleby Group	Brockram	Collyhurst Sst	Breccia	Sandstone	0 - 220m
		Unconformity; Variscan deformation, uplift and erosion					
CARBONIFEROUS	363	Coal Measures			Siltstone, mudstone, sandstone and coal		<1500m
		Hensingham Group and Millstone Grit			Siltstone, mudstone, sandstone and thin limestone		50 - 2500m
		Carboniferous Limestone	(Sellafield Site) Urwick Limestone, Frizington Limestone, Martin Limestone, Basal Beds		Limestone, siltstone, mudstone and sandstone		200 - 5000m
Devonian	409	Unconformity, late Caledonian (Acadian) deformation and intrusions, uplift and erosion					
SILURIAN	439	Windermere Supergroup	Kendal Group		Cleaved sandstone, siltstone and mudstone		<4500m
			Coniston Group				<2000m
			Tranearth Group				<1100m
			Stockdale Group				<150m
			Deer Group		Calcareous siltstone and limestone		30 - 300m
ORDOVICIAN	510	Unconformity; granite and granodiorite intrusion, including Eskdale and Ennerdale intrusions					
		Borrowdale and Eycott Volcanic Groups	(Sellafield Site) Fleming Hall Formation, Brown Bank Formation, Birdwatch Formation, Broom Farm Formation, Knockstone Bank Formation		Extrusive and intrusive basalt, andesite, dacite pyroclastic and volcaniclastic rocks		<8000m (>1140m in Sellafield Site)
		Unconformity; period of uplift and erosion					
		Skiddaw Group			Strongly cleaved sandstone, siltstone and mudstone		c. 5000m

NIREX

Geological sequence in the Sellafield region
(Ages after a 'Geologic Time Scale' by Harland et al., Cambridge University Press, 1990)

5.1



Key

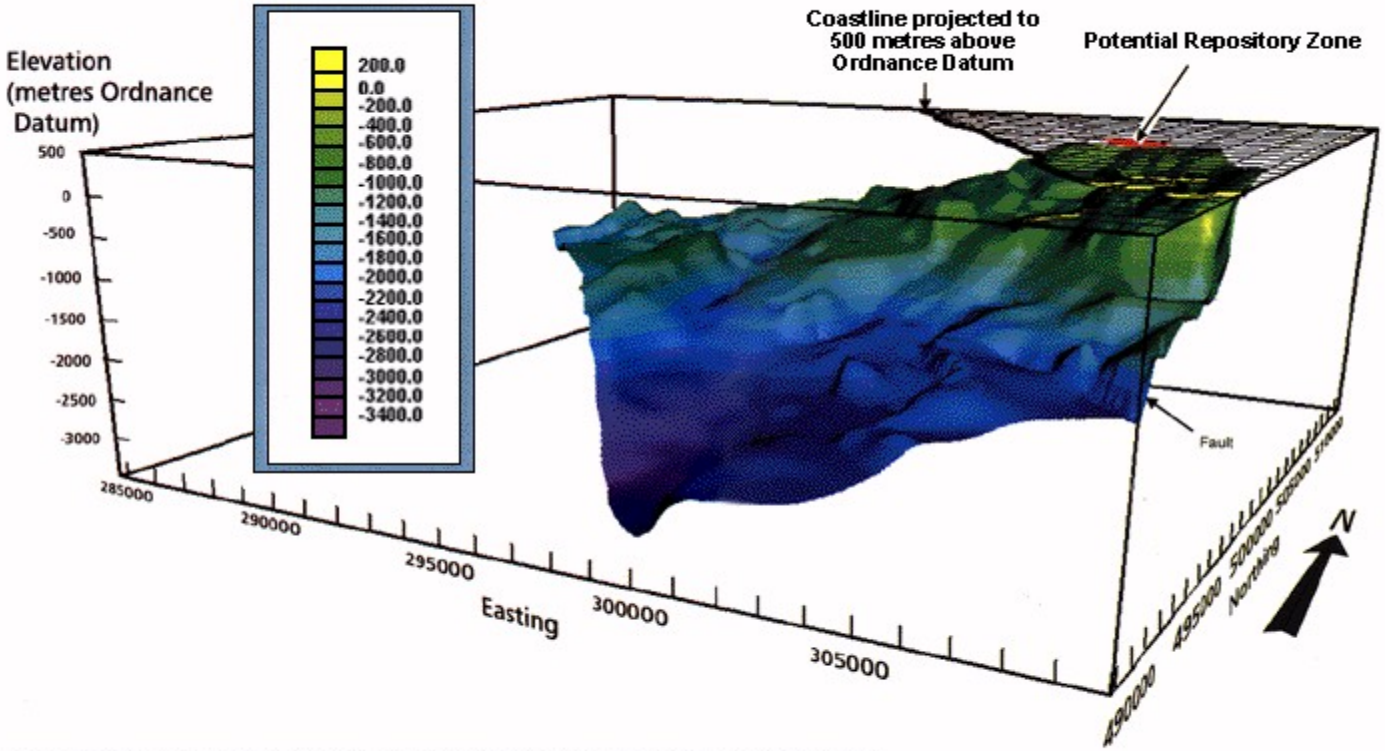
- Quarternary
- Calder Sandstone
- St. Bees Sandstone Formation
- Brockram
- Brockram, St. Bees Shale and St. Bees Evaporite (undivided)
- Carboniferous

} Sherwood Sandstone Group

- Fleming Hall Formation, (undivided)
- Longlands Farm Member
- Sides Farm Member
- Town End Farm Member
- Borrowdale Volcanic Group below Fleming Hall Formation
- Borrowdale Volcanic Group (undivided)

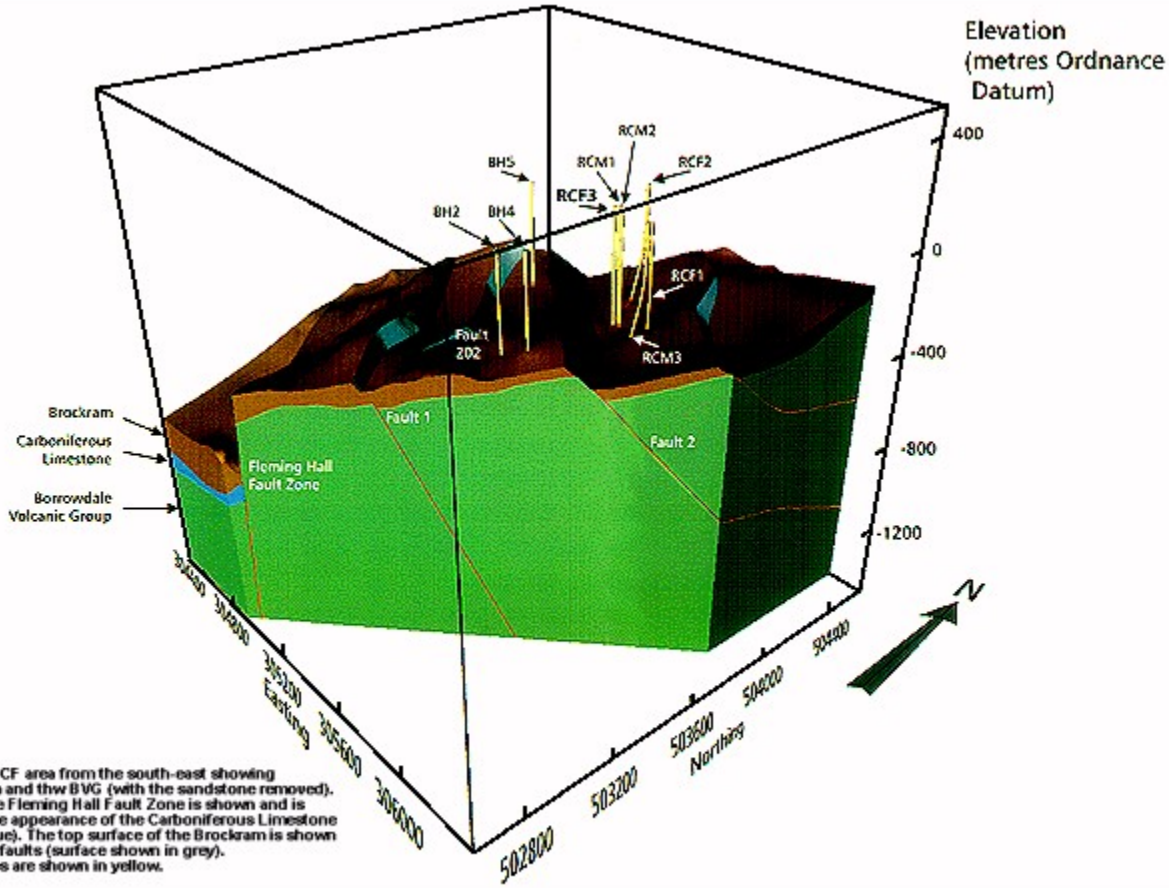
} Borrowdale Volcanic Group

NIREX	Title Cross-section through Potential Repository Zone	Figure No. 5.2



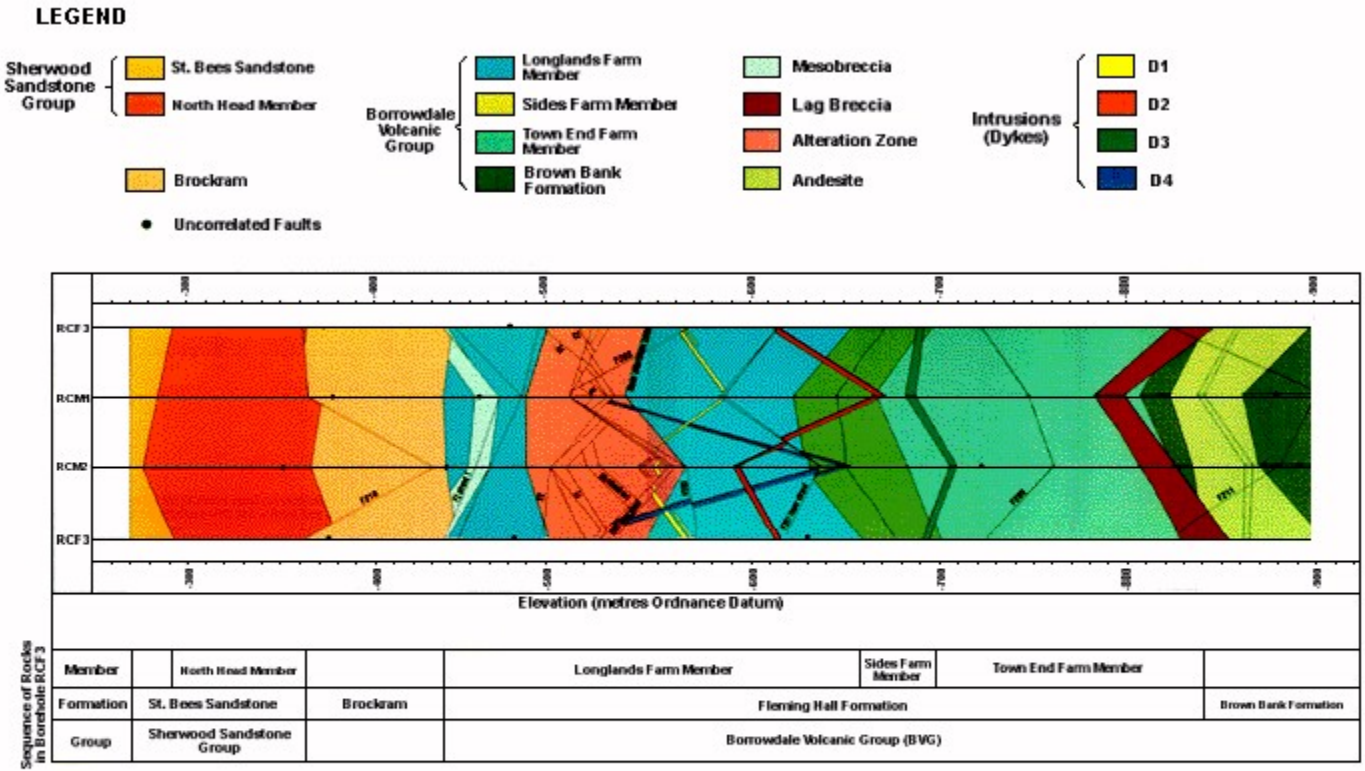
Three dimensional view from the south-east of the 'District' area (approximately 20km by 30km) showing the shape of the surface marking the top of the Basement. The colour shades mark 200 metre verticle intervals. The sharp changes in slope in the foreground are faults displacing the top of the Basement.

NIREX	Title	Three-dimensional representation of top Basement in the Sellafield 'District' area	Figure No. 5.3



View of the RCF area from the south-east showing the Brockram and thw BVG (with the sandstone removed). To the left the Fleming Hall Fault Zone is shown and is marked by the appearance of the Carboniferous Limestone (shown in blue). The top surface of the Brockram is shown displaced by faults (surface shown in grey). The boreholes are shown in yellow.

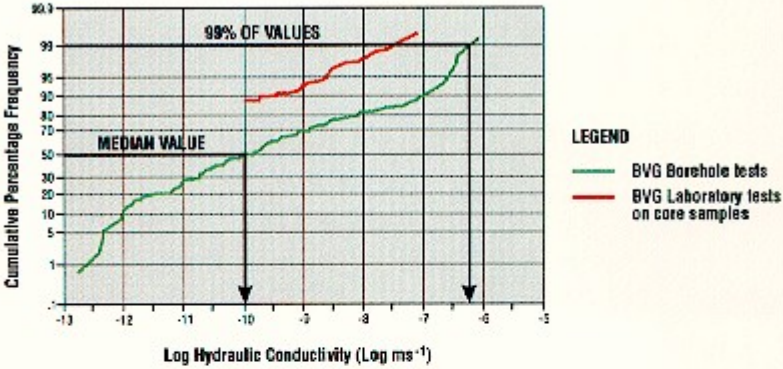
NIREX	Title Three-dimensional geological model of the RCF area	Figure No. 5.4



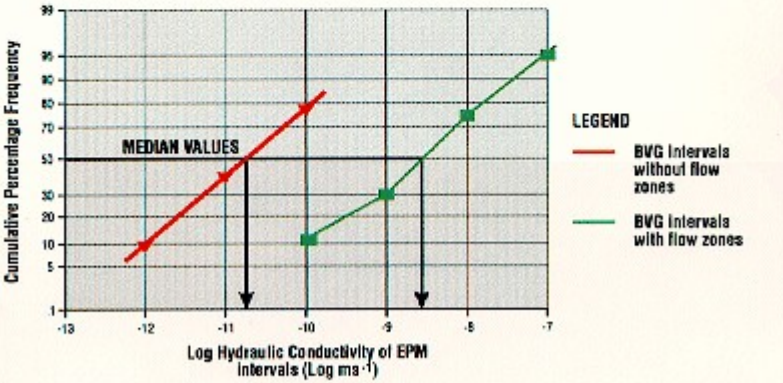
The section shown is between Boreholes RCF3, RCM1 and RCM2. It shows the various geological members within the BVG, the intrusive rocks and the position of the main faults based upon an interpretation of the borehole and geophysical data

NIREX	Title	Geological structure of the proposed area of the Rock Characterisation Facility	Figure No. 5.5

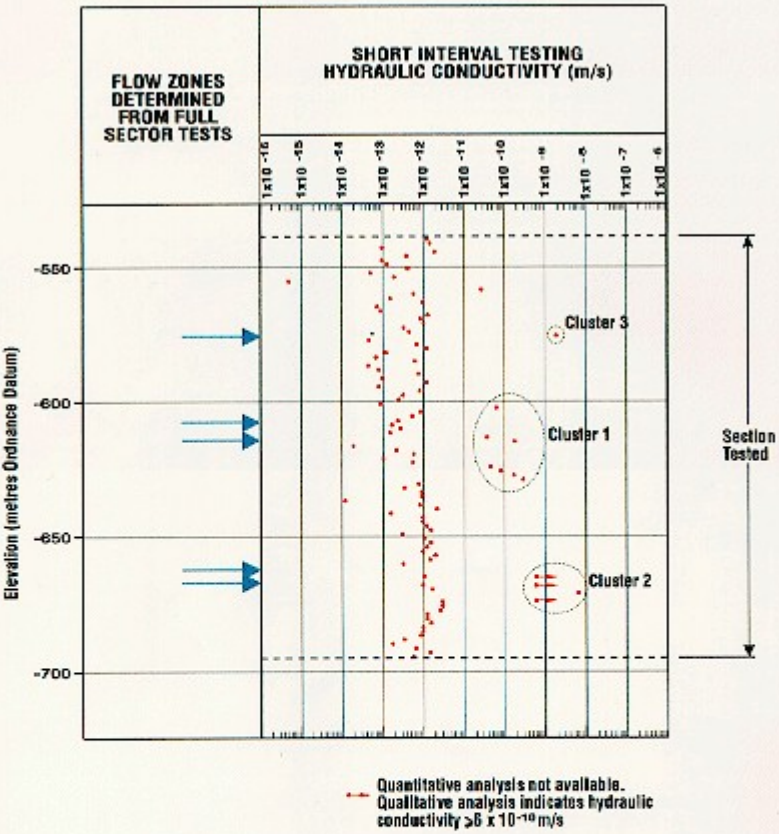
a) Distribution for BVG from 50 metre borehole sections and as measured in the laboratory on small core samples



b) Distribution for 50 metre borehole sections divided into sections with and without flow zones

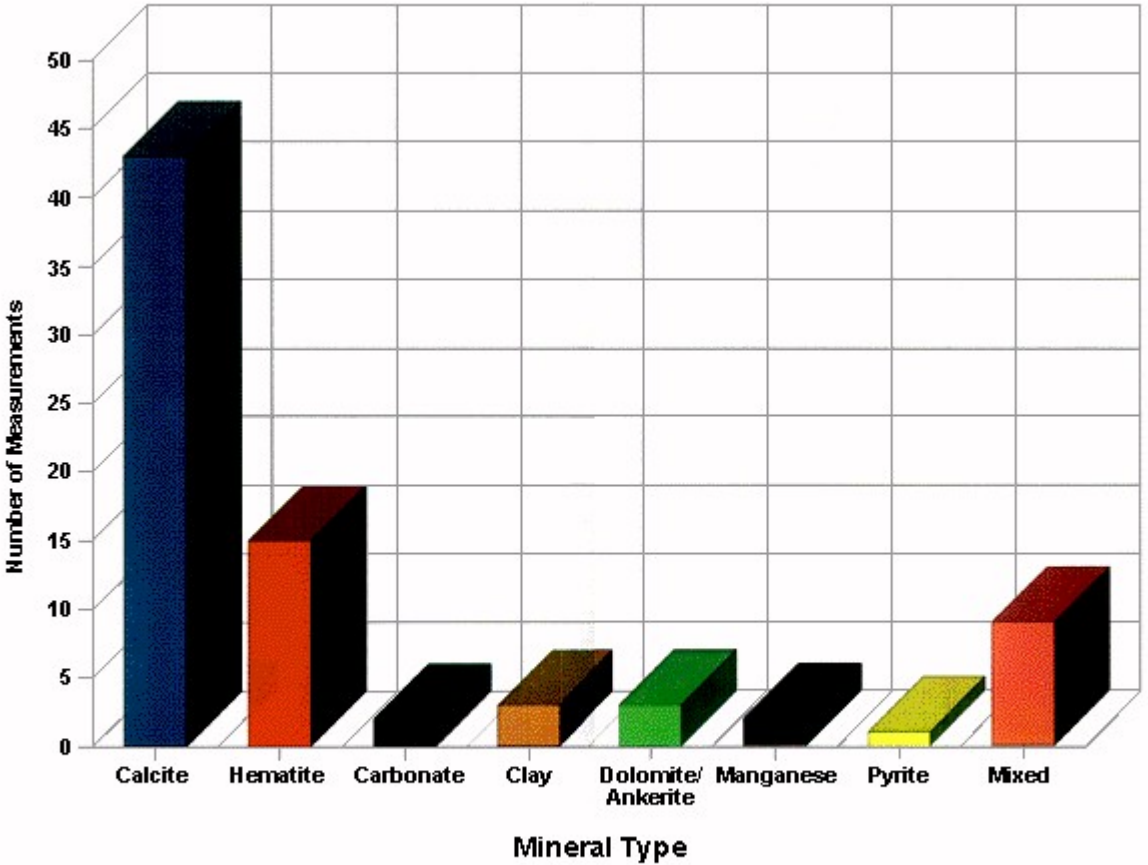


NIREX	Title Summary of hydraulic conductivity values	Figure No. 6.1

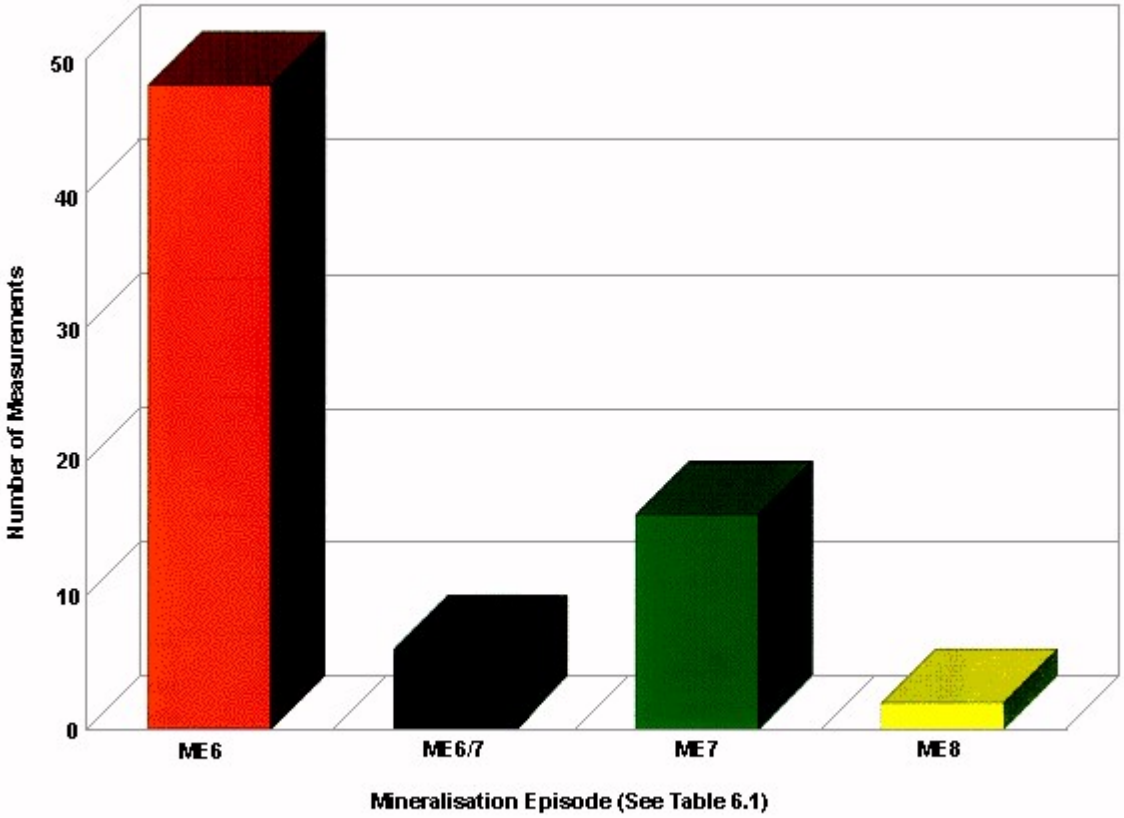


NOTE:
For full details see Drawing No. 10089 in Nirex Report No. SA/95/002

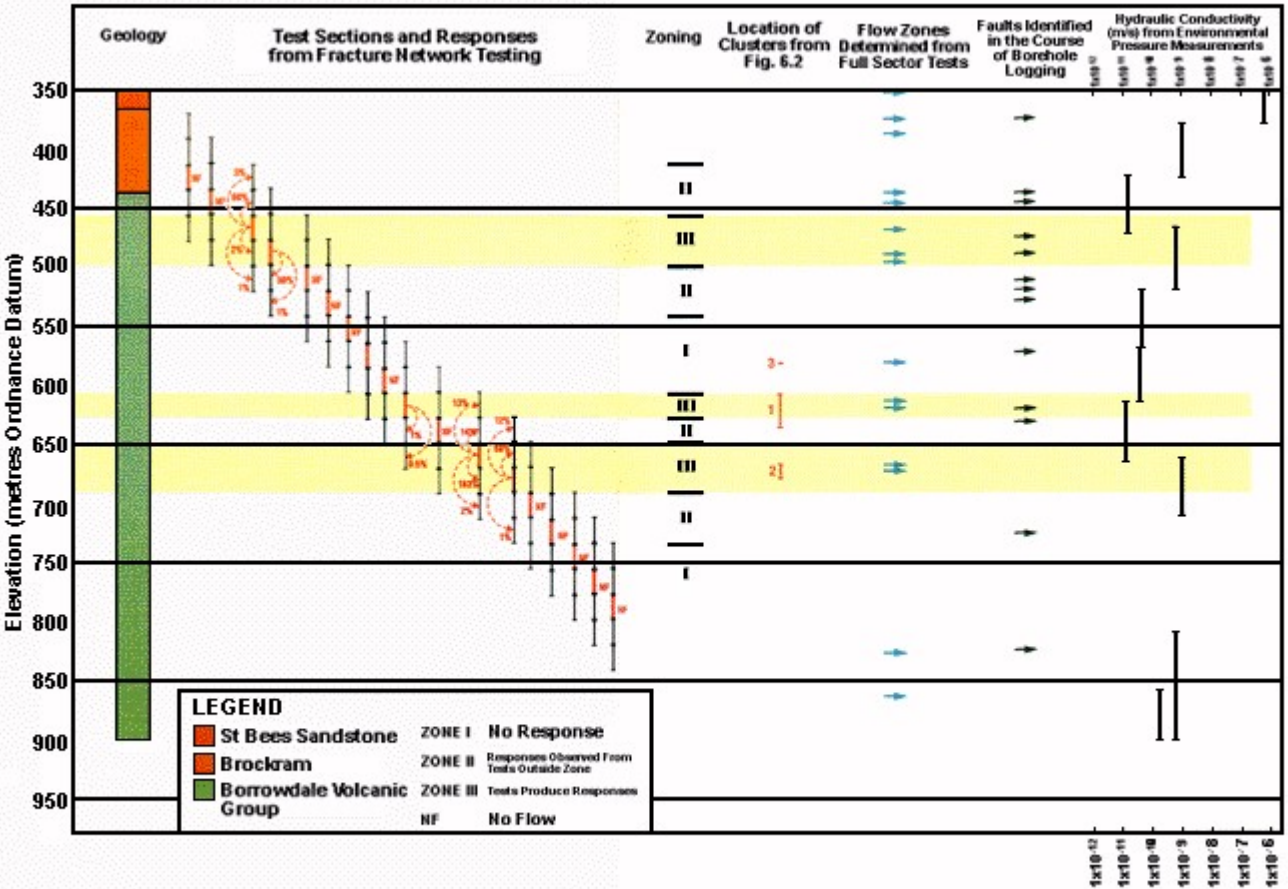
NIREX	Title Hydraulic conductivity values for Short Interval Hydraulic Testing	Figure No. 6.2



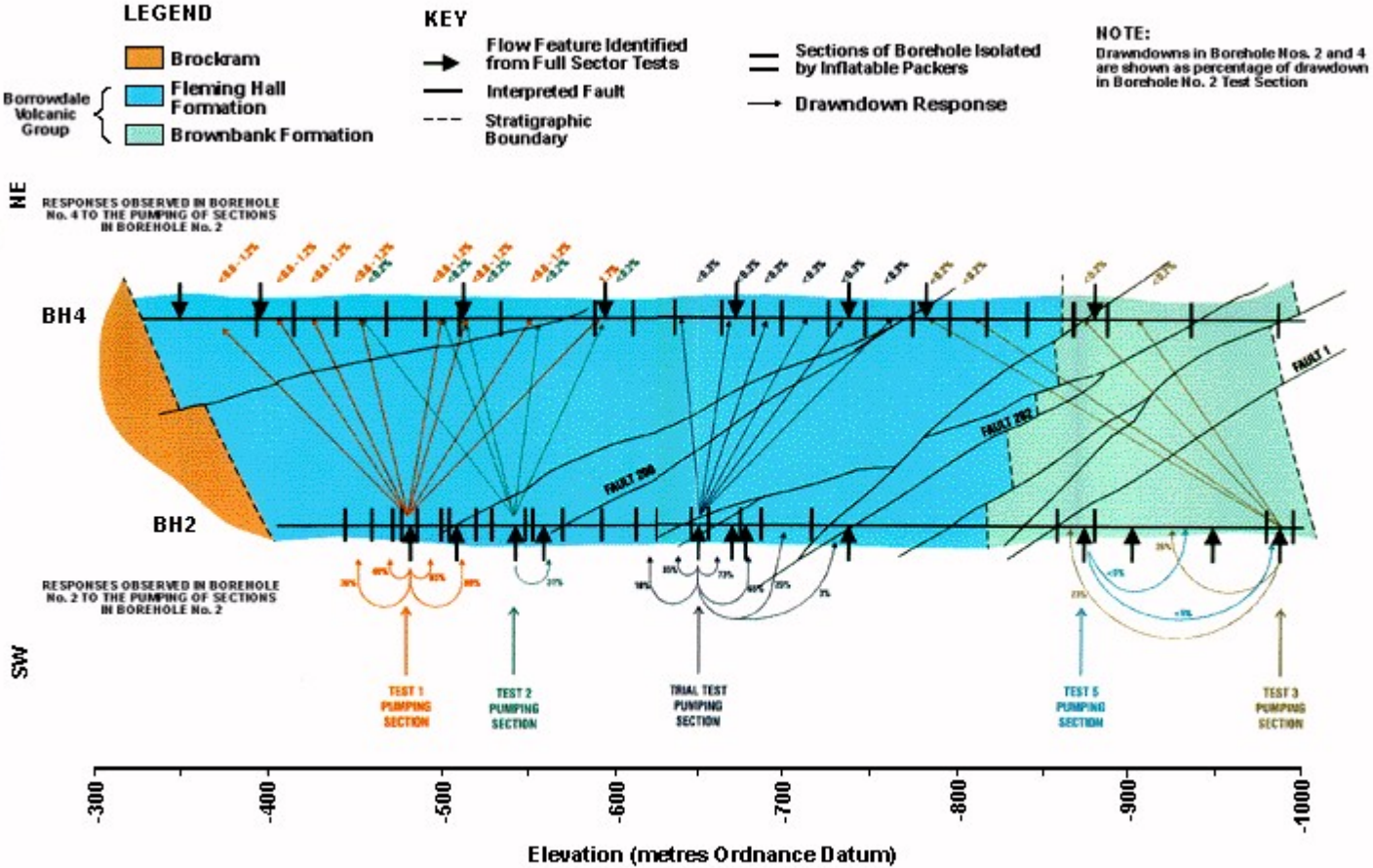
NIREX	Title	Flow zones: distribution of infill material	Figure No. 6.3



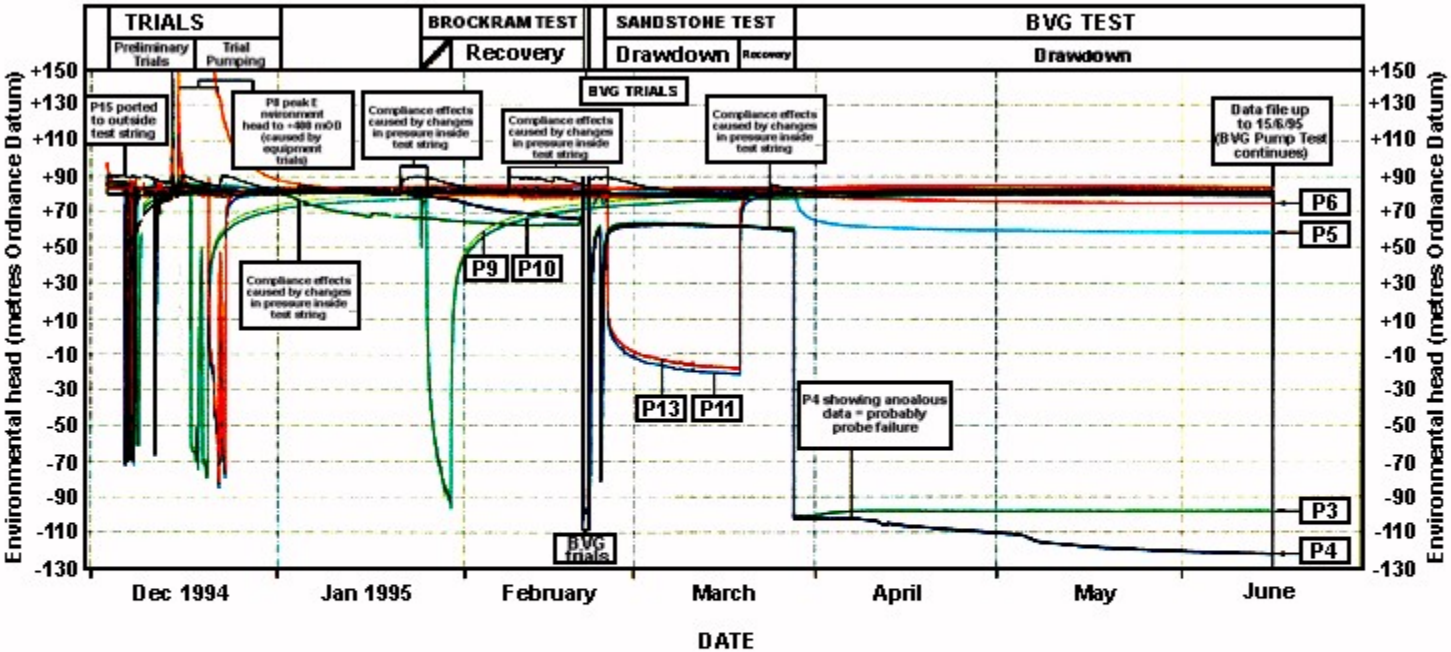
NIREX	Title Flow zones: distribution of mineralisation episode	Figure No. 6.4



NIREX	Title	Figure No.
	Fracture Network Testing: observed responses and flow zones	6.5

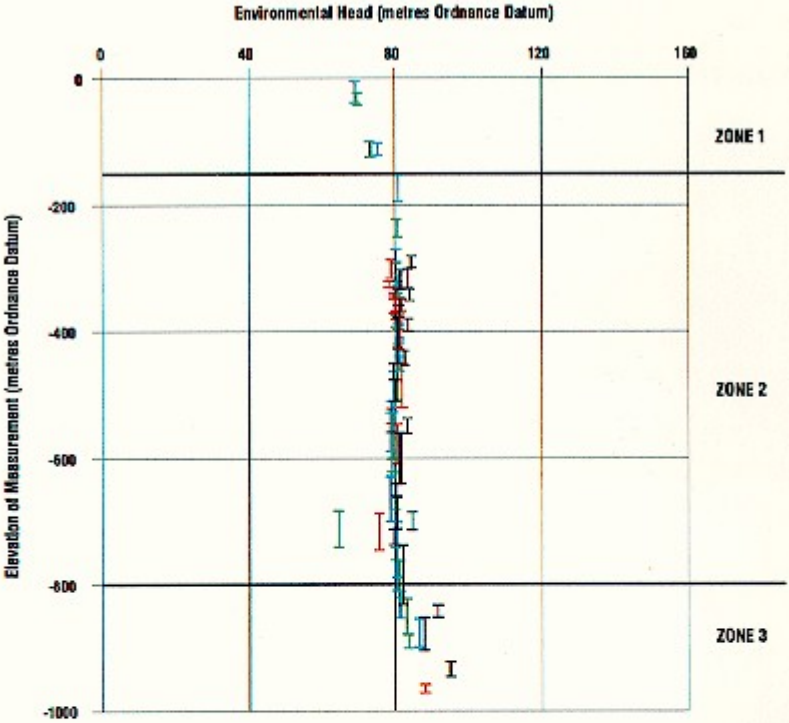


NIREX	Title Results of Cross-Hole Hydraulic Testing in Boreholes 2 and 4	Figure No. 6.6



NOTE:
For full details see Drawing No.10192 in Nirex Report Number SA/95/002

NIREX	Title	Figure No.
	Results of Borehole RCF3 Pump Test	6.7



ZONE 1 - Heads increase with depth (Upward gradient)

ZONE 2 - Heads constant with depth (No vertical gradient)

ZONE 3 - Heads increase with depth (Upward gradient)

NOTE:
Data derived from Groundwater Monitoring Network

NIREX	Title Groundwater heads in RCF/RCM Boreholes	Figure No. 6.8