CHAPTER 26

THE INVESTIGATIONS OF THE GEOLOGY AND HYDROGEOLOGY AT SELLAFIELD IN THE UNITED KINGDOM

Robert Chaplow

United Kingdom Nirex Limited, Harwell, Oxfordshire OX11 0RH, UK

26.1 INTRODUCTION

United Kingdom Nirex Limited (Nirex) is responsible for providing and managing a national disposal facility for solid intermediate-level (ILW) and low-level (LLW) radioactive waste. Such wastes have been produced in the UK for over 40 years and have come from the nuclear power industry, medical and defense establishments, as well as from other research and industrial sources. UK Government policy is to dispose of these wastes in a deep underground repository. Similar policies are followed by other countries which produce substantial quantities of long-lived radioactive waste.

Following an extensive site selection exercise, Nirex announced in 1989 that it would investigate, initially, sites at Dounreay in Caithness and Sellafield in Cumbria, to establish their suitability as safe locations for a deep disposal facility for ILW and LLW. Initial boreholes and other geological and geophysical surveys subsequently indicated that the geology at both sites had the potential to meet the demanding safety requirements for a deep repository. In July 1991, Nirex announced that it was to concentrate its further investigations at Sellafield. Given that there appeared to be little otherwise to distinguish between the overall suitability of the two sites, transport of waste and the associated costs were major considerations in this decision; an estimated 60 per cent by volume of the radioactive waste destined for the repository arises from British Nuclear Fuels'operations at Sellafield.

This paper presents a broad overview of the investigations carried out at Sellafield, up to approximately the end of 1994 and of the results obtained. A description is provided of the strategy being adopted for the continued investigation of the site. Descriptions of the geology, hydrogeology and geochemistry studies at Sellafield are provided by Michie (1996), Sutton (1996), and Bath, et al., (1996).

26.2 SCOPE OF INVESTIGATIONS

26.2.1 Scientific Approach

Nirex has adopted a systematic scientific approach to the design and implementation of the investigations. Awide range of technical specialists and techniques have been used in the conduct of the work and care has been taken to avoid undue reliance on any single technique in the interpretation of the ground conditions. The quality of the work being undertaken by Nirex has been recognized by independent reviewers, for example, by the Royal Society Study Group (1994) and RWMAC (1994).

Nirex makes information from the investigations widely available through publications and presentations. A series of papers on the geology of the Sellafield area were presented at a meeting of the Yorkshire Geological Society in late 1993) and subsequently published (Holliday and Rees, 1994). A second meeting on the hydrogeology was held at the Geological Society Apartments in May 1994, the papers presented at this meeting have been submitted for publication. Nirex also releases a significant number of detailed reports on the results of the investigations (For example: Nirex, 1992 Nirex, 1993a-i, Nirex, 1994a-b). An independent panel of university professors carries out review of the work undertaken by Nirex. The first Annual Report of this review panel was released in December 1994.

26.2.2 Areas of Study

The studies carried out in West Cumbria have been contained within three areas (Fig. 26.1):

1. An area onshore and offshore (A) 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, using exist-

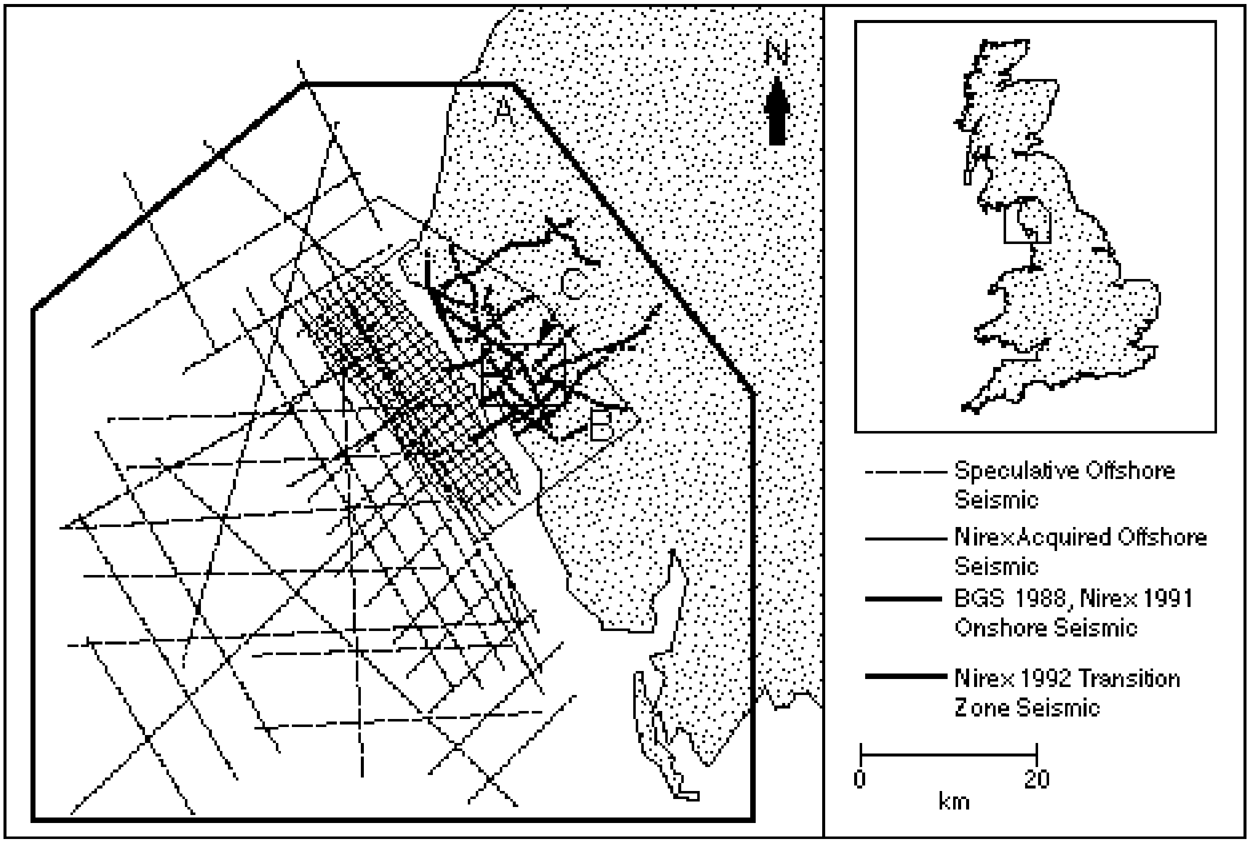

Figure 26.1. Investigation areas showing location of seismic surveys.

ing published sources of information and commercially available offshore seismic survey data. Additional data, including structural geological data relevant to seismic hazard studies, were collected from wider areas.

2. An area (B) of approximately 20 km by 30 km within which geological features have direct relevance to the 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.
3. An area (C) immediately around the potential repository covering an area of approximately 50 km^2 and within which all the Nirex deep boreholes are located.

26.2.3 Regional Surveys

The extent of the regional geophysical surveys commissioned or acquired by Nirex is shown in Figure 26.1. These surveys have included some 1,950 line kilometres of seismic reflection, both onshore and offshore, and 8,500 km of airborne magnetic and radiometric surveys. Gravity data has been collected along many of the seismic lines. Geological mapping has been carried out by the British Geological Survey and regional surveys of near-surface hydrogeological features have been commissioned, as have remote seismic studies. Monitoring of springs, river gauging and meteorological observations are continuing. A programme of work to characterize the Quaternary deposits of the area has commenced.

26.2.4 Boreholes

By December 1994 Nirex had drilled twenty one deep boreholes (Fig. 26.2). Many of these were around 1,000 metres deep, with the deepest, Borehole 2, extending to 1,950 metres depth. Several phases of drilling have been completed, namely:

- An initial pattern of boreholes (Boreholes 1, 2, 3, 4, 5, 7, 10, 11, 12 and 14) to obtain an understanding of

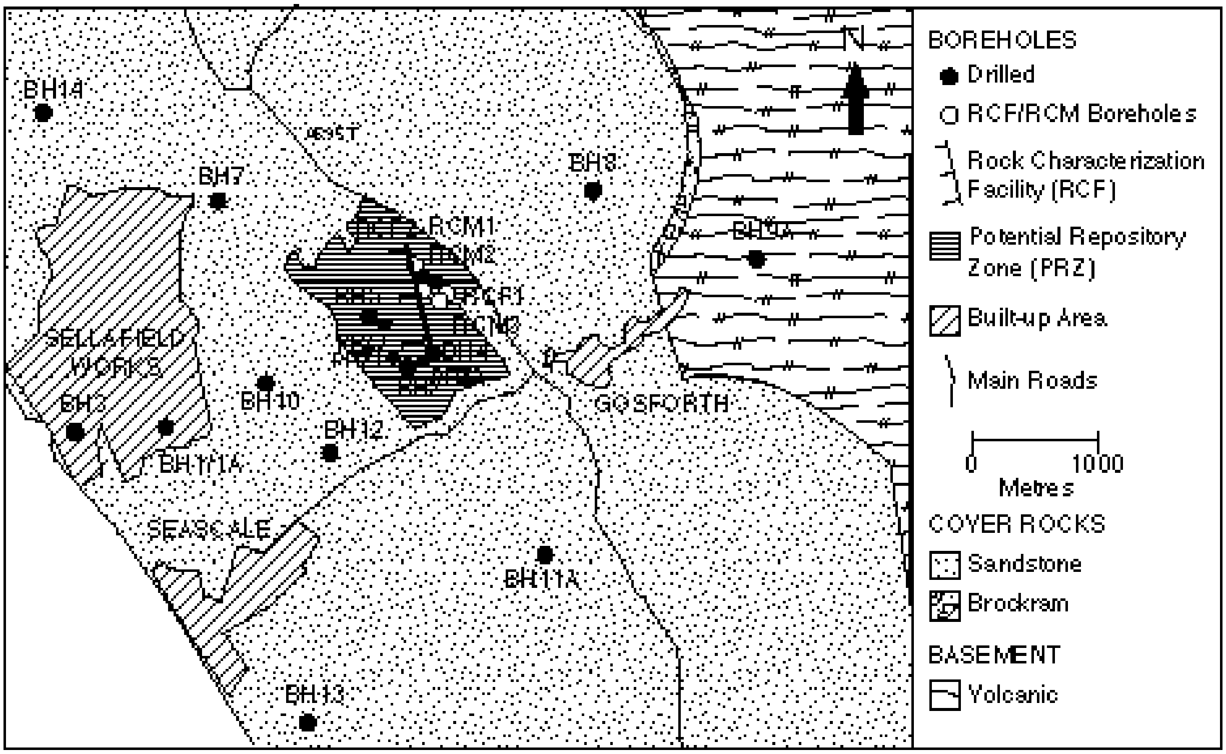

Figure 26.2. Schematic location of Nirex boreholes within the Sellafield site area, December 1994.

the regional geological and hydrogeological setting of the site.

- A subsequent series of boreholes to investigate specific aspects of the site. Boreholes 8 and 9 have been drilled in the upper part of the catchment to investigate groundwater recharge and Borehole 13 has investigated the area to the south where the thickness of the Permo-Triassic sequence increases markedly.
- Aseries of six boreholes (RCF1 to 3) and RCM1 to 3 have been drilled in the area of the proposed Rock Characterization Facility to characterize the ground in advance of underground excavation and to permit installation of a groundwater monitoring system close to the proposed shafts (Nirex, 1994b).
- Inclined boreholes are being drilled to characterize parts of the potential repository zone. Boreholes PRZ2 and 3 are completed; PRZ1 has still to be completed.

Two boreholes, drilled by others several decades ago for mineral exploration purposes, have been instrumented to supplement the groundwater monitoring system.
The majority of the drilling carried out by Nirex has been to obtain continuous core which is used for detailed characterization of the rock penetrated. Geophysical logging is also carried out to determine rock properties and particularly 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 hydraulic conductivity of the rocks, that is, their ability to transmit water. Testing is carried out during breaks in the drilling and after completion of drilling to investigate the hydraulic properties of the rocks at a range of scales (Fig. 26.3).

Sampling of groundwater and analysis of samples is routinely undertaken during drilling and subsequently. Special measures are taken to reduce the levels of contamination of the groundwater by drilling fluids and to quantify the extent of any contamination to permit the determination of groundwater chemistry.

The completed boreholes are also used for undertaking specialist testing programmes. Examples include cross-hole seismic tomography and cross-hole hydraulic testing. A major programme of pump testing to measure the responses of the groundwater system over a wide area to

Field Activity	Scale	Hydraulic Characteristics	Hydraulic Connections to Overlying Units	Calibration/ Validation	Transport Processes
Standard Well Testing	10m	●	●		
Borehole 2/4 crosshole	100-500m	●	Partially		
Fracture Network Testing	10-100m	●			
Short Interval Testing	1-5m	●			
RCF3 Pump Test	Up to km		●	●	
PRZ Monitoring Network	All		●		
Tracer Tests	10-100m			●	●
RCF	All			●	●

Figure 26.3. Types of hydrogeological testing.

pumping from a central borehole is currently in progress.

26.2.5 Long-Term Monitoring

Most of the boreholes have now been converted for long-term monitoring of groundwater pressures by the installation of Westbay multi-level groundwater monitoring systems. These systems permit measurements of groundwater pressures within selected sections of the boreholes. Many sections are now equipped with automatic logging systems which provide measurements of pressures at two minute intervals to a high level of precision (Nirex, 1994a).

Nineteen boreholes have Westbay strings installed, and a further borehole is equipped with an alternative monitoring system. Some of the monitoring strings are amongst the most complex and deepest instrumentation systems of their type ever installed.

The monitoring network is designed to establish baseline groundwater conditions and to provide the means for monitoring the response of the groundwater system to induced perturbations, such as from cross-hole testing, pumping tests and RCF shaft excavation.

26.3 SUMMARY OF RESULTS

26.3.1 Geology

The proposed repository host rock at Sellafield comprises the volcanic rocks of the Ordovician Borrowdale Volcanic Group. Within the potential repository zone, the top surface of volcanic rocks is at a depth of 400 to 600 metres, occurring beneath the immediately overlying Permian breccia, the Brockram (Fig. 26.4). This is in turn, overlain by the Triassic Sandstones of the Sherwood Sandstone Group. The top of the volcanic rocks dips to the west such that at the coast they are some 1,600 metres below the surface. On approaching the margins of the East Irish Sea Basin, the Sherwood Sandstone Group is underlain by a thicker sequence of Permian rocks comprising the St. Bees Shale, the St Bees Evaporite and the Brockram. These are in turn underlain by the Carboniferous Limestone which rests unconformably on the Borrowdale Volcanic Group rocks (Michie, 1996; Holliday and Rees, 1994).

The rocks have been subjected to numerous periods of faulting and folding during their geological history. The distribution of the various formations at depth and the locations of the faults which cut them have been defined primarily by interpretation of the seismic reflection data, calibrated by the deep boreholes and utilizing mine plan data for the area to the north of Sellafield. Structure contour maps covering areas A and B have been generated for all the major geological boundaries within the sequence (Nirex, 1993a, b). Within the potential repository zone, additional detail is now being added based upon further boreholes, seismic reflection surveys, cross-hole tomography surveys between sets of co-planar boreholes and complex analysis of existing vertical seismic profiling (VSP) data.

26.3.2 Hydrogeology

Much of the work being undertaken by Nirex at

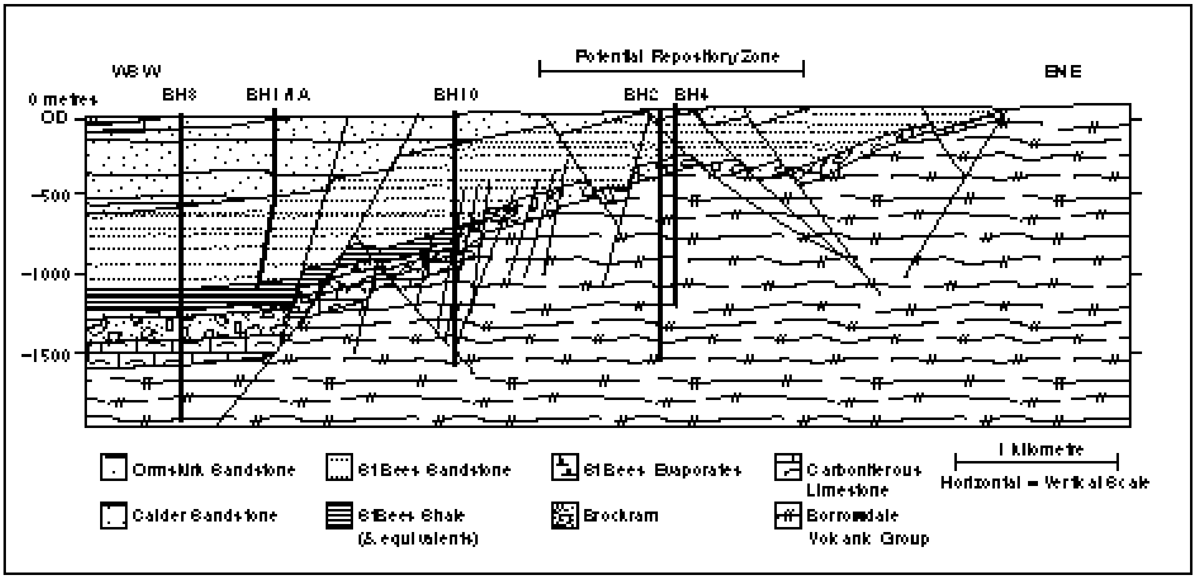

Figure 26.4. Schematic geological WSW-ENE cross-section through the Sellafield area.

Sellafield has been focused on determining the hydrogeology of the site, given that the flow of groundwater is recognized as the dominant mechanism for transport of radionuclides from a repository back to the surface (Nirex, 1993i; Black and Brightman, 1996).

Measurements have been made of hydraulic properties, especially heads and conductivities in boreholes. Having recognized that the flow of groundwater through the volcanic rocks is principally through fractures, effort has been directed towards characterizing those fractures which are both open and inter-connected such that they are hydrogeologically significant.

Geochemical studies of the groundwater have provided an independent record of past flow and mixing, and hence geochemical studies have featured prominently in the work undertaken (Bath, et al., 1996). Finally, numerical modeling has been extensively used to develop the understanding of the processes which are controlling-groundwater flow (Heathcote, et al., 1996).

The hydraulic conductivity of the rocks was initially determined in the boreholes using 50 metre long contiguous sections. Within the Borrowdale Volcanic Group the conductivity values are typically very low (Fig 26.5) with half the values measured over 50 metre lengths in the boreholes being less than $1x10^{-10}$ ms, including tests over faulted and fractured zones.

In order to identify the distribution of the hydrogeologically significant fractures in the parts of the sequence dominated by fracture flow, production tests have been carried out over the full lengths of boreholes, often in a series of stages. Inflow of water into the borehole is induced by imposing a drawdown in the order of 100 metres head and identifying flow zones by production logging. In many cases flows are so low as to preclude the effective use of spinner logging, zones only being identified from differential temperature and conductivity logging (Fig 26.6). Individual fractures, or groups of fractures, which carry flow are characterized by reference to the core logs and the borehole imaging geophysical logs.

Most of the fractures intersected by the boreholes have no detectable flow. Flowing fractures are therefore relatively widely spaced. Just over 150 have been identified in over 20,000 metres of drilling. Studies are currently being undertaken to characterise them.

Although fractures encountered in particular boreholes can make a major contribution to the conductivity of the rock mass in the immediate vicinity, it is the extent to which conducting fractures are connected which will determine groundwater flow in the Borrowdale Volcanic Group. Cross-hole seismic tomography has helped to define the geological structure between adjacent boreholes.

The extent of the connectivity is being examined using single borehole fracture network testing, cross-hole

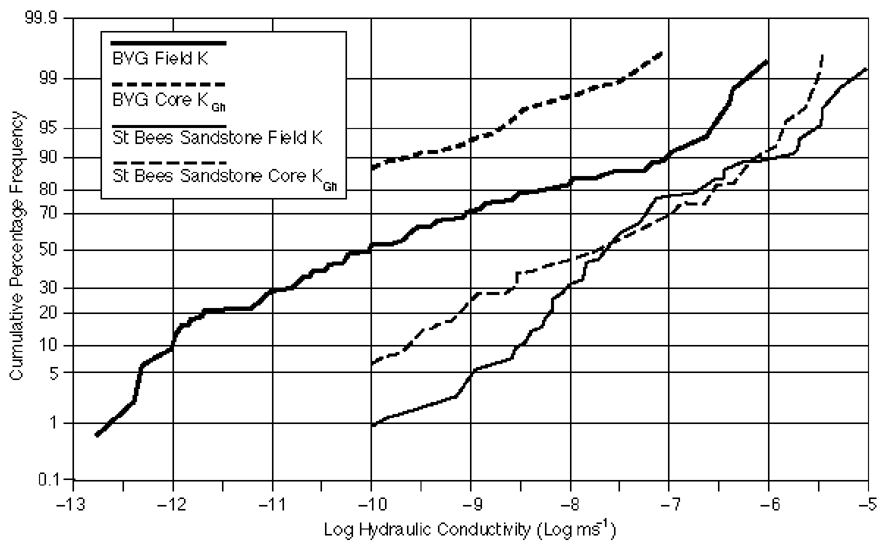

Figure 26.5. Summary of hydraulic conductivity values.

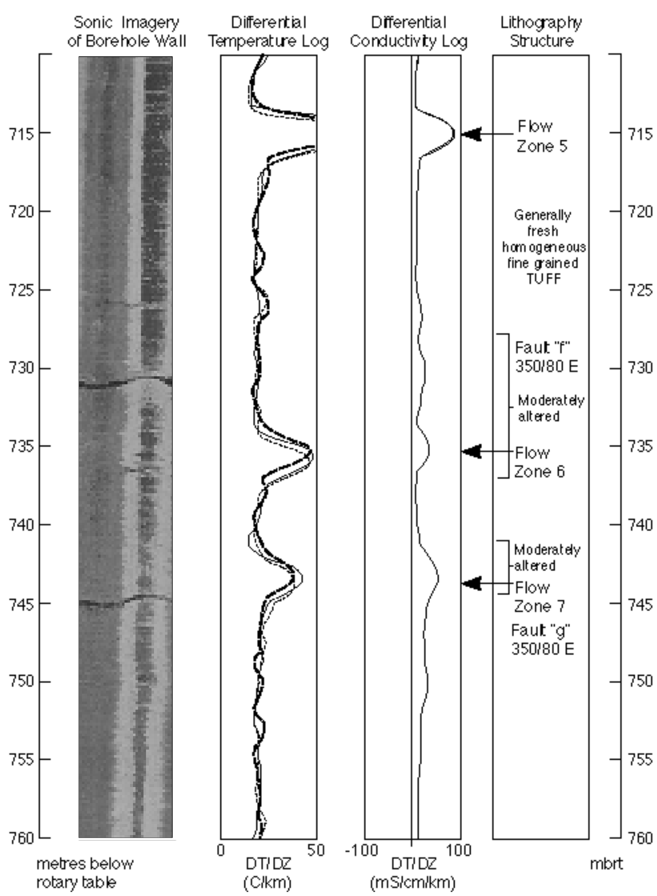

Figure 26.6. Identification of flow zones in Borehole 2.

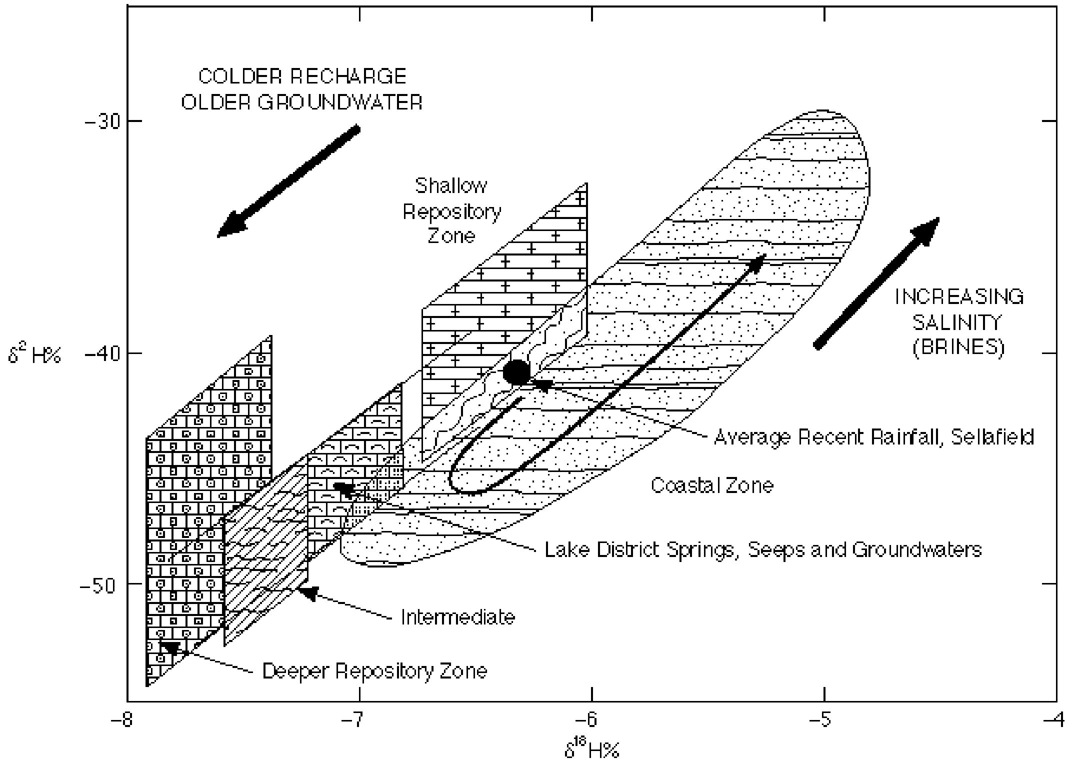

Figure 26.7. Stable isotopic discrimination between groundwaters with different origins.

hydraulic testing and by a series of large scale pump tests. Preliminary results from recent testing suggest that the fracture network may be less well connected than previously considered to be the case.

26.3.3 Geochemistry

Geochemical studies (Bath, et al., 1996) are carried out for three reasons: (a) to support the development of a conceptual model of the present-day hydrogeology, (b) to investigate how the groundwater system has evolved over time; and (c) to characterize the baseline hydrochemical conditions to support other studies.

Considerable progress has been made and the present dataset has contributed substantially to the construction of a conceptual model of the hydrogeological system, on which numerical modeling can be based. Some hydrochemical aspects of the conceptual model (particularly salinity sources and mixing zones) will provide specific tests of the adequacy of numerical modeling.

The palaeohydrogeology of the area is dominated by its location on the margin of the East Irish Sea Basin. The influence of basinal brines has been a feature of the deep sediments and the Borrowdale Volcanic Group basement in the west of the area for considerable geological time. Within the potential repository zone, a range of analyses including stable isotopic and noble gas temperature data for groundwaters in the Borrowdale Volcanic Group basement suggests that the waters at depth are clearly distinguishable from the shallow groundwaters and from modern rainfall (Fig. 26.7), and that the deeper waters probably have long residence times. This is a consistent pattern shown by several independent determinants and studies (Bath, et al., 1996).

26.3.4 Hydrogeological System

The current conceptual model of the hydrogeological system is illustrated in diagrammatic form in Figure 26.8. The three component parts of the system: the Irish Sea Basin Regime, the Hills and Basement Regime, and the Coastal Plain Regime are essentially as defined in mid 1992 (Nirex, 1992), although greater confidence in this model has been obtained with the availability of geochemical data.

The conceptual model and its evolution are supported, not only by geological, hydrogeological and geochemi-

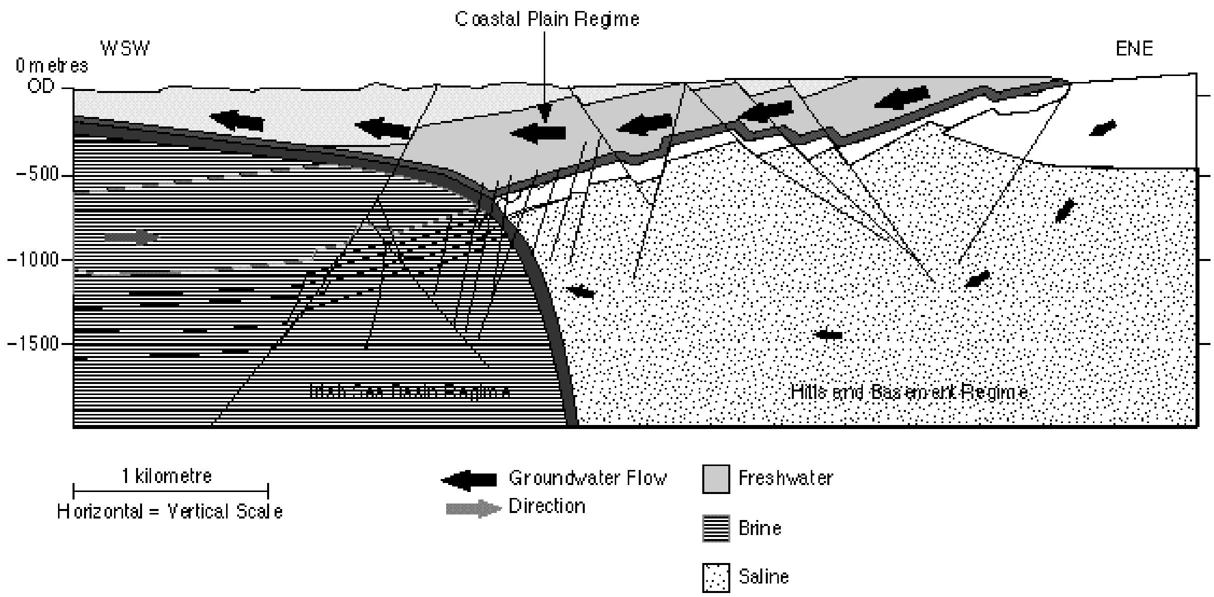

Figure 26.8. Current conceptual model of the groundwater system in the Sellafield area.

cal studies, but also by a range of numerical modeling studies which have served to examine and test a series of concepts concerning the behavior of individual components of the total system (Heathcote, et al., 1996).

26.4 FURTHER STUDIES

The investigations carried out to date from the surface are providing Nirex with a good understanding of the geological and hydrogeological conditions at Sellafield as they affect the decision on whether or not the site will be suitable for the construction of a repository to meet the stringent regulatory safety targets. Further investigations from the surface are in progress or are planned to further characterize specific features of the site. In particular, the pump test in Borehole RCF3 and the continued monitoring of groundwater conditions utilizing the installed instrumentation system are important components of this forward programme.

Investigations from the surface are, however, unable to resolve all the remaining uncertainties regarding the characteristics of the site. Nirex, in line with similar agencies in other countries, considers that a phase of investigations carried out underground from a suitably constructed experimental facility is a logical and essential extension to characterization from the surface. For this reason, Nirex has applied for planning permission to construct an underground Rock Characterization Facility (RCF) at the Longlands Farm site at Sellafield. This application is the subject of an appeal by Nirex against refusal, by Cumbria County Council, of planning permission.

26.5 CONCLUSIONS

The following conclusions are drawn from the investigations carried out at Sellafield:

1. An extensive programme of investigations has been carried out by Nirex. Various independent reviewers have commented on the high quality of the work undertaken.
2. The geological succession and structural geology of the site has been determined in significant detail.
3. Cross-hole seismic tomography has demonstrated that the geological structures can be mapped between boreholes. This observation is providing added confidence regarding the definition of the geological structure within the Borrowdale Volcanic Group and its influence on the hydraulic conductivity of the rock mass.
4. Preliminary quantitative assessments have been made of the distribution of hydraulic conductivity values in all the major hydrogeological units. Values measured in the Borrowdale Volcanic Group are typically low.
5. A limited number of individual fractures has been identified in the Borrowdale Volcanic Group along which groundwater flows. These fractures form a network which controls the flow of water through the rocks. Nirex is currently assuming that the fracture

network is well connected. Preliminary results from recent testing suggest that the fracture network may be less well connected than previously considered to be the case.

6. Geochemical and isotopic analysis of groundwater samples have assisted the development of the hydrogeological conceptual model and are helping to give some indication of the age and provenance of the groundwater within the Borrowdale Volcanic Group rocks. Evidence is suggesting that the deeper groundwater in the potential repository zone is old.
7. Good progress has been made with the investigations, and with the interpretation and modeling studies which follow on, to determine whether or not the site is suitable as a potential repository. However, much work remains to be done to resolve uncertainties and to develop confidence in the understanding of the site and the models which are constructed to represent its behavior. Construction of an underground Rock Characterization Facility forms a logical and essential continuation to the investigations carried out from the surface to progressively reduce uncertainty and to provide the information necessary to determine the suitability of the site for construction of a deep radioactive waste repository to meet the stringent regulatory safety requirements.

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