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May 1994

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Prepared for Swedish Nuclear Fuel and Waste Management Co.

ABSTRACT

The objective of this report is to summarize AECL's strategy for surface-based geotechnical site investigations used in screening and evaluating candidate areas and candidate sites for a nuclear fuel waste repository and for the development of geosphere models of sites. The report is one of several prepared by national nuclear fuel waste management programs for the Swedish Nuclear Fuel and Waste Management Co. (SKB) to provide international background on site investigations for SKB's RD&D programme on siting.

The scope of the report is limited to surface-based investigations of the geosphere, those done at surface or in boreholes drilled from surface.

The report discusses AECL's investigation strategy and the methods proposed for use in surface-based reconnaissance and detailed site investigations at potential repository sites. Site investigations done for AECL's Underground Research Laboratory are used to illustrate the approach. The report also discusses AECL's strategy for developing conceptual and mathematical models of geological conditions at sites and the use of these models in developing a model (Geosphere Model) for use in assessing the performance of the disposal system after a repository is closed. Models based on the site data obtained at the URL are used to illustrate the approach. Finally, the report summarizes the lessons learned from AECL's R&D program on site investigations and mentions some recent developments in the R&D program.

ABSTRACT (Swedish)

Syftet med denna rapport är att sammanfatta AECL:s strategi för geotekniska platsundersökningar från markytan, använda vid lokalisering och utvärdering av kandidatområden och kandidatplatser för ett kärnavfallsförvar och för utveckling av geosfärsmodeller för platser. Rapporten är en några rappporter som skrivits av nationella kärnavfallsprogram för Svensk Kärnbränslehantering AB, i syfte att ge internationell bakgrund om platsundersökningar för SKB:s program för lokalisering.

Rapportens omfattning begränsar sig till ytbaserade undersökningar av geosfären, det vill säga undersökningar utförda på markytan och i borrhål från markytan.

I rapporten diskuteras AECL:s undersökningsstrategi och de föreslagna metoderna för ytbaserad rekognosering och detaljerade platsundersökningar på potentiella förvarsplatser. De platsundersökningar som genomförts för AECL:s underjordiska forskningslaboratorium (Underground Research Laboratory, URL) används som exempel på tillämpning. Rapporten diskuterar även AECL:s strategi för utveckling av konceptuella och matematiska modeller av geologiska förhållanden på platser och hur dessa modeller används vid framarbetandet av en geosfärsmodell för analys av förvarssystemets funktion efter förslutning. Modeller baserade på data från URL har använts för att illustrera tillvägagångssättet. Slutligen sammanfattar rapporten de lärdomar som erhållits inom AECL:s F&U-program för platsundersökningar samt noterar några nya utvecklingsområden inom F&U-programmet.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 NUCLEAR FUEL WASTE MANAGEMENT IN CANADA

In 1978, the governments of Canada and Ontario established the Nuclear Fuel Waste Management Program " . . . to assure the safe and permanent disposal" of nuclear fuel waste (Joint Statement 1978). Atomic Energy of Canada Limited (AECL) was made responsible for research and development (R&D) on disposal and Ontario Hydro was made responsible for studies on interim storage and transportation of used fuel. The purpose of the R&D on disposal was to " . . . verify that permanent disposal in a deep underground repository in intrusive igneous rock is a safe, secure and desirable method of disposing of radioactive waste."

In 1981, the governments limited AECL's mandate with a decision that no site selection would be done until the disposal concept was accepted and that no organization would be given responsibility for site selection and disposal operations until after the disposal concept was accepted (Joint Statement 1981).

The used fuel from Canada's power reactors is currently stored safely in water-filled pools or dry storage concrete containers. The concept developed for disposal is to place the waste in long-lived containers; emplace the containers, enveloped by sealing materials, in a repository excavated at a nominal depth of 500 to 1000 m in intrusive igneous (plutonic) rock of the Canadian Shield; and seal all the excavated openings and exploration boreholes to form a passively safe system. Multiple engineered and natural barriers (the container, the very low-solubility waste form, the repository seals, and the geosphere) will protect humans and the natural environment from contaminants in the waste.

The acceptability of the disposal concept is now being reviewed under the federal Environmental Assessment and Review Process. The Panel appointed for the review has issued guidelines to identify the information that should be provided by AECL (Federal Environmental Assessment Review Panel 1992). After the Panel has received and reviewed the information requested from AECL and from other parties, it will hold public hearings and make recommendations to assist the governments in reaching a decision on the acceptability of the disposal concept and on the steps that should be taken to ensure the safe long-term management of nuclear fuel waste in Canada.

1.2 R&D OBJECTIVES OF CANADIAN SITE INVESTIGATIONS

An important objective of the R&D on the disposal concept has been the development, evaluation and demonstration of methods and technology

- to identify potentially suitable areas, called candidate areas, for locating a repository within large regions containing plutonic rock (site screening) and
- to identify potentially suitable sites for a repository, called candidate sites, within each candidate area and determine if the candidate sites are technically suitable (site evaluation).

Because transport in groundwater is the most likely mechanism by which contaminants in the nuclear fuel waste could escape the repository and reach the biosphere, the main objectives of the site investigations in the Canadian R&D program have been

- to develop an understanding of groundwater flow and contaminant transport in plutonic rock,
- to investigate natural features and processes controlling migration of radionuclides in the geosphere, and
- to develop and demonstrate a methodology for using geotechnical data in performance assessment (including the development of conceptual models of site conditions and computer codes for simulating groundwater flow and contaminant transport in the geosphere).

1.3 STATUS OF SITE INVESTIGATIONS

AECL has been developing and testing methods and equipment for geotechnical site investigations at plutonic rock sites on the Canadian Shield since 1975. Work has been done at five field research areas (White Lake, Chalk River, East Bull Lake, Atikokan, and Whiteshell) located in different structural subprovinces of the Canadian Shield (Figure 1-1).

The research areas have provided access for borehole investigations in a variety of plutonic rock types and geologic settings, including a range of structural complexity. In addition, more general investigations involving only surface reconnaissance without drilling of boreholes have been done at many other locations on the Shield. Most of the site investigations have been concentrated on the East Bull Lake, Atikokan and Whiteshell Research Areas.

The White Lake Research Area is located on a fine- to medium-grained, massive to highly foliated, biotite granite pluton in a gneissic metamorphic terrain of the Grenville Province. The White Lake Research Area was active for only one year and has not been used since 1976.

The Chalk River Research Area is located on folded quartz monzonitic orthogneisses and paragneisses of the Grenville Province. The work at Chalk River was discontinued in 1983.

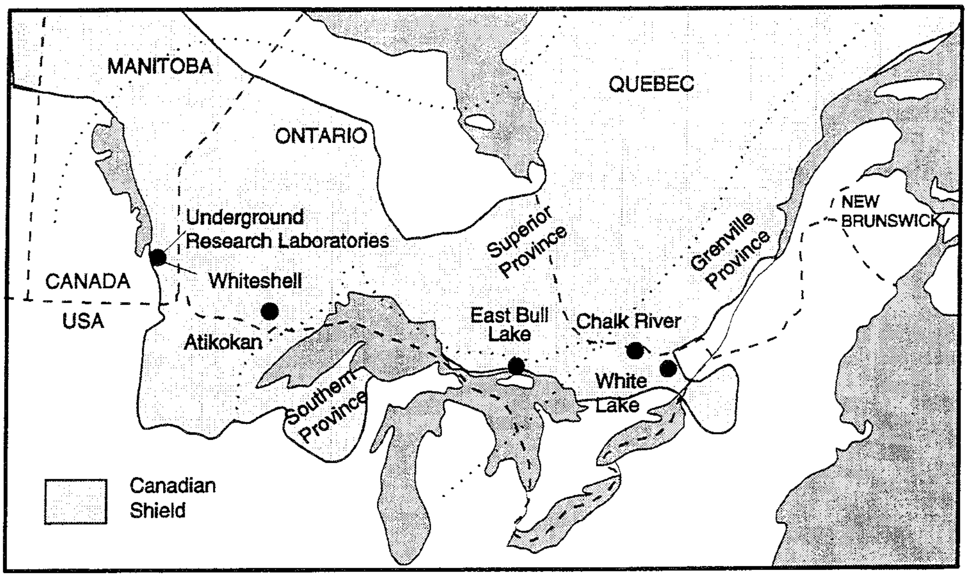

Figure 1-1. Location of Field Research Areas.

The East Bull Lake Research Area is centred on the East Bull Lake pluton, an Early Proterozoic layered gabbro-anorthosite complex which intrudes metamorphosed granite, syenite and metavolcanic rocks of the Superior Province near the junction of the Superior, Grenville and Southern Provinces. Hydrogeologic conditions were monitored at the East Bull Lake Research Area from 1983 through 1992.

The Atikokan Research Area is centred on the Eye-Dashwa Lakes pluton, an elliptical, 70 km^2 body of coarse-grained, biotite-hornblende granite in the Superior Province near the contact between the Wabigoon and Quetico subprovinces. Although no new investigations are being undertaken at the Atikokan Research Area, routine long term monitoring of hydrogeologic and meteorologic conditions is continuing.

The Whiteshell Research Area is centered on the Lac du Bonnet Batholith, a large granitic intrusion in the Winnipeg River batholithic subprovince of the Superior Province. Work is still continuing at the Whiteshell Research Area to provide long-term data on hydrogeologic, hydrogeochemical and hydrologic conditions.

Field research on site investigation methods began at the White Lake Research Area with aeromagnetic surveys in 1975. These surveys were followed in 1976 by a few shallow cored boreholes and borehole television surveys. In 1977, simultaneous investigations were begun at the Chalk River and Whiteshell Research Areas, on AECL property at the Chalk River Laboratories and Whiteshell Laboratories respectively. Investigations at the Atikokan and East Bull Lake Research Areas were initiated in 1979 and 1981 respectively.

The early research at Chalk River and Whiteshell was aimed mostly at developing and testing the equipment and methods to measure the physical and chemical characteristics of plutonic rocks at a relatively small size scale and within individual boreholes. Since then the research has evolved in two directions. One direction has been toward developing methods to determine the characteristics of plutonic rocks and their surroundings at the more regional scale (500 to 1000 km^2) and up to 1.0 km in depth (Betcher and Pearson 1982, Davison et al. 1994a). The other direction has been toward developing site investigation methods for use in or from underground excavations, in particular methods to assess near-field changes in the characteristics of the rock caused by the construction and operation of a repository (Everitt et al. 1994).

Most of the near-field research has been performed in AECL's Underground Research Laboratory (URL) constructed on the Lac du Bonnet Batholith at the Whiteshell Research Area (Simmons and Soonawala 1982, Simmons 1988). Construction of the URL began in 1984 and continued until 1990. The lease for the URL has recently been extended to the end of 2011.

Investigations aimed at characterizing large scale groundwater flow systems in plutonic rock terrain began in 1984 at the Atikokan Research Area (Pearson 1984) and in 1986 at the Whiteshell Research Area (Davison et al. 1989). The surface-based investigations at the Whiteshell Research Area have covered primarily a 500 km^2 area of the Lac du Bonnet Batholith and have involved borehole investigations at five small grid areas in addition to the URL and Whiteshell Laboratories sites. The work has included the drilling, testing and monitoring of 32 boreholes to depths exceeding 250 m, 14 of these to depths of 500 m to 1000 m.

2 SURFACE-BASED SITE INVESTIGATIONS

2.1 BACKGROUND AND SITING PROCESS

Disposal of nuclear fuel waste in a repository would proceed in sequential stages: siting, construction, operation, decommissioning, and closure. AECL believes that for disposal to be implemented successfully in Canada, the involvement of potentially affected communities would be required throughout all stages, and activities such as impact management, characterization, monitoring, design, and environmental assessment would be ongoing. Consequently, AECL has developed a siting process that allows the integration of public involvement with the identification of technically suitable sites by thorough site investigations.

The effectiveness of community involvement would depend on the degree to which trust was established between the communities and the organization implementing disposal. No organization has yet been given a mandate for disposal in Canada. Consequently, in its submission to the Environmental Assessment Review Panel, AECL will discuss how it would approach siting and how it believes the organization eventually made responsible for disposal should approach siting (AECL in preparation). AECL believes that the implementing organization should be open and fair in its relationships with all potentially affected communities and that a special relationship (including a basis for shared decision making) should be negotiated with the host community (potential host communities until a site was selected and approved). The decision of a community to be considered as a potential host (and eventually to be the host) should be voluntary.

The siting stage is the time during which technically suitable potential candidate sites for safe disposal would be identified and evaluated to select a preferred site. Approval to construct a repository at the preferred site would be sought using a repository design for that site and an assessment of the potential effects of disposal at that site.

In Canada, there are currently about 900 000 used fuel bundles in storage (about 17 000 Mg U). Recent cost estimates for disposal have been based on repositories with capacities of 5 million bundles and 10 million bundles. Repositories with these capacities would require disposal areas of about 2 km^2 and 4 km^2. The disposal area that is required affects the size of the areas that need to be investigated during siting; those shown in Table 2-1 and Figure 2-1 are for a repository with a disposal area of about 4 km^2.

Siting would be divided into two substages: site screening and site evaluation. Initially, attention would focus on relatively large regions containing potentially suitable plutonic rock bodies in the vicinity of potential host communities, that is, communities that were willing to participate in the siting process.

Table 2-1. Areas for Investigation During Siting.

Scale	Area (km^2)	Duration (a)	Type of Investigation
			<u>Site Screening</u>
Regional	greater than 1000	2 - 5	- analysis of existing data - reconnaissance
			<u>Site Evaluation</u>
Candidate Area	greater than 400	3 - 5	- reconnaissance - surface studies - subsurface studies using boreholes drilled from surface at a number of small study areas (grid areas of 1-2 km^2)
Candidate Site	about 25	4 - 9	- detailed surface studies - detailed subsurface studies using boreholes from surface and possibly exploratory excavation
Repository	about 5	4 - 8	- detailed underground studies in exploratory shafts and tunnels and using boreholes drilled from them

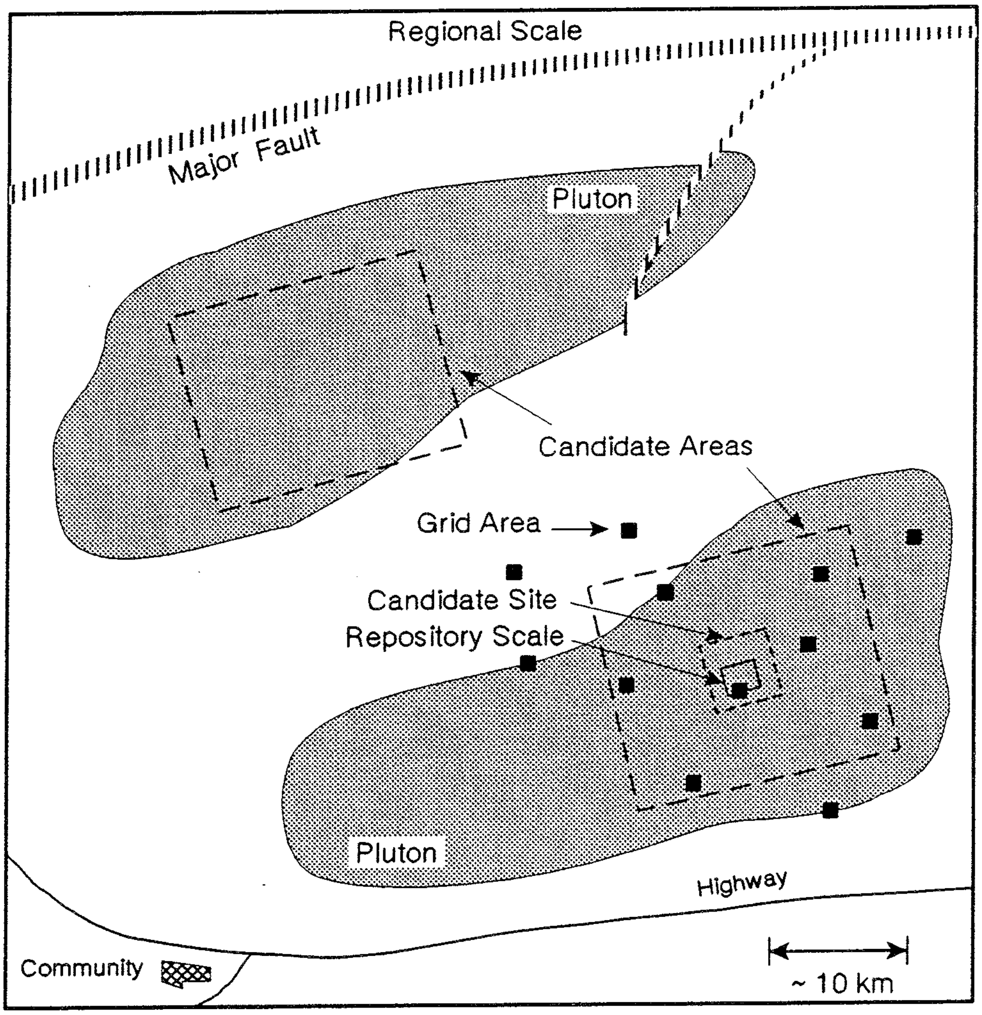

Figure 2-1. Scales of Investigations.

The objective during site screening would be to identify, in consultation with potential host communities, a small number of potentially suitable candidate areas for evaluation.

The objective during site evaluation would be to locate, in consultation with potential host communities, a potentially suitable candidate site in each candidate area and, from the candidate sites, to select a preferred site for the repository.

Underground site investigations would begin after locations for exploratory shafts had been identified at the preferred site. Underground site investigations are not discussed in this report.

2.2 INVESTIGATION STRATEGY

2.2.1 Introduction

At the beginning of the siting stage, regions of the Canadian Shield containing potentially suitable plutonic rock bodies would be identified (siting regions). Thereafter, the approach would be to progressively narrow the geographic focus of the site investigations. During the site screening substage potential host communities would be sought in the siting regions. Technically suitable potential candidate areas would be sought in the vicinity of the potential host communities, from which a small number of candidate areas would be selected for evaluation. During the site evaluation substage, candidate sites containing potential repository locations would be identified in the candidate areas, from which a preferred site and repository location would be selected (Table 2-1 and Figure 2-1).

This progressive focusing of the site investigations corresponds with a progressively greater commitment of resources by the organization responsible for implementing disposal. Initially, during site screening, relatively large amounts of information about large areas would be obtained at relatively low cost. Existing reports, records, topographic maps, satellite images, air photos, and reconnaissance surveys of rock properties and hydrological and environmental conditions would be analyzed. Additional information would be obtained by reconnaissance investigations if necessary. The technical information would be presented in map form in relation to the location of existing societal infrastructure such as towns, roads, railway lines, electrical transmission lines, and natural gas pipelines.

A small number of candidate areas would be selected for evaluation. Initially during site evaluation, additional reconnaissance investigations would be done. More expensive, detailed investigations on the ground and in boreholes would be undertaken when uncertainties could be reduced no further using information from reconnaissance investigations. The detailed investigations would be done first at a number of small study areas (grid areas) associated with each remaining candidate area to identify a candidate site. Additional detailed investigations would be carried out at each candidate site. If the investigations indicated that a candidate site was not technically suitable, it would no longer be a candidate.

A preferred site for the repository would be selected from the remaining candidate sites when additional surface-based investigations were no longer cost effective at providing information needed to confirm the technical suitability of the candidate sites. At the preferred candidate site, investigations in and from very expensive exploratory shafts and tunnels would provide detailed information that could not be obtained from surface-based investigations. The objectives of the excavation-based investigations would be to confirm the suitability of the site for a repository and to obtain information needed to apply for approval to construct the repository.

2.2.2 Site Screening Substage

Initially the objective of site investigations would be to identify at least one potentially suitable candidate area in the vicinity of each potential host community.

The technical strategy for achieving this objective would be to compile and analyze pre-existing information (Section 2.3) and to conduct limited reconnaissance investigations within regions of plutonic rock (Section 2.4.2)

- to identify regions of low seismic risk,
- to identify regions of low economic resource potential where the likelihood of future exploration drilling intersecting a repository would be low,
- to identify regions of low regional and local topographic relief where the driving force for groundwater flow could be inferred to be low,
- to identify features (major lineaments) that could be inferred to be potential major transport pathways through the rock (faults or fracture zones),
- to identify large areas between the major lineaments that could be inferred to have low permeability at depth, and
- to identify indicators of in situ stress and anisotropy in the properties controlling groundwater flow and geomechanical response in the rock.

Areas with low local relief that contain few, widely-spaced, major lineaments would be favored. Initially, the areas of plutonic rock with the most favorable topographic relief and distribution of lineaments would be selected as potential candidate areas. If there were many potential candidate areas identified, they would need to be ranked in consultation with the potential host communities to select a small number of candidate areas for evaluation.

2.2.3 Site Evaluation Substage

The objectives of reconnaissance investigations (Section 2.4) at the candidate areas would be

- to identify the features in or near each candidate area that should be the focus of the more detailed investigations (which would be conducted at surface and in boreholes at a number of smaller grid areas);
- to decrease the uncertainty in the inferred nature of the major lineaments and the volumes of rock between them; and
- to confirm that the characteristics of the relatively large candidate areas selected during site screening were favorable for siting a repository, making it worth the increased commitment of resources for more detailed investigations.

The objective of the detailed grid area investigations would be to identify a potentially suitable location for the repository (a candidate site) within the candidate area. This would involve thorough surface investigations and subsurface investigations in boreholes (Section 2.5)

- to identify locations of recharge and discharge for groundwater flow systems at scales (local, intermediate, regional) relevant for transport of contaminants from the repository to the biosphere; and
- to identify and characterize volumes of rock with significantly different litho-structural, fracture, geomechanical, hydrogeological and geochemical characteristics (domains).

If the area contained no suitable location (or was not as promising as other candidate areas), the investigations could be abandoned at an early stage without further commitment of resources. If the candidate area appeared to contain potentially suitable sites, the investigations could lead to the identification of a candidate site.

Preliminary safety assessments, using models of the site conditions developed from the integrated interpretation of the information from the site investigations, would contribute to the judgement on potential suitability.

2.3 COMPILATION AND ANALYSIS OF EXISTING INFORMATION

2.3.1 Sources of Existing Information

During site screening geotechnical and environmental factors would be addressed primarily by analyzing already existing data. In Canada, there is a wealth of information available, such as satellite and airborne imagery; airborne geophysical surveys; reports and maps on geology, soils, hydrology, water resources, forestry, wildlife, and agriculture; inventories of exploratory drill holes or domestic water supply wells; and seismic monitoring records.

Satellite images are available for all of Canada. Landsat Multispectral Scanner (MSS) imagery is available which provides 80 m spatial resolution and four spectral wavelength bands between 0.50 and 1.10 μm. Landsat Thematic Mapper (TM) data is also available with a ground resolution of 30 m for six spectral wavelength bands between 0.45 and 12.5 μm. A seventh Landsat TM thermal infrared band is available with 120 m resolution. The combination of Landsat MSS and TM data provides a wide range of spectral data and spatial resolution for geological, hydrologic and environmental analyses. Better spatial resolution in satellite imagery is available from the French SPOT satellite which has a 10 m resolution from its panchromatic sensor. SPOT can also image areas in stereo. In addition, synthetic aperture radar (SAR) images are now available from the ERS-1 satellite with a spatial resolution down to 12.5 m. It can provide images of an area from two look directions.

Natural Resources Canada (NRCan) has published topographic maps at the scales of 1:1 million, 1:500 000, 1:250 000 and 1:50 000 for almost all of the Canadian Shield. In addition, the Geological Survey of the Ontario Ministry of Natural Resources (OMNR) has published topographic maps at 1:20 000 scale for many areas of the Shield in Ontario. Similar maps exist for the Shield areas of Quebec and Manitoba from provincial agencies. The Geological Survey of Canada (GSC, a part of NRCan) has compiled geophysical maps showing the total magnetic field and Bouguer gravity at the scale of 1:1 million for virtually all of the Shield and airborne magnetic data is available at scales of 1:250 000 and 1:50 000 for much of the Shield. Airborne electromagnetic (EM) and gamma-ray spectrometry data is also available for many areas from the GSC, OMNR and from other provincial mining or geological agencies. Aerial photography is available at a variety of scales.

There is a wealth of information available in reports and publications from the extensive geological mapping and mineral exploration that has been undertaken across the Canadian Shield. Extensive files of geological reports and maps for the Canadian Shield in Ontario are available both from the GSC and OMNR. AECL used such information early in the research program to prepare a map and inventory of over 1000 plutonic rock bodies in Ontario at a scale of 1:1 million (McCrank et al. 1981). In addition, the GSC has prepared regional geological compilations at a scale of 1:50 000 for much of Ontario.

Records of seismic activity are available from the GSC. Monitoring of seismic activity as part of the Canadian National Seismic Monitoring Network began in eastern Canada in the 1930's. Seismic zoning maps of Canada are prepared from these records to aid the engineering and construction industries in assessing seismic hazard in different regions of the country (Basham et al. 1985). AECL supported the installation of six additional seismograph stations on the Canadian Shield in Ontario in 1982. This has allowed the accurate detection of very small seismic events in the Ontario portion of the Canadian Shield.

There is also considerable information available from various federal and provincial government departments about climate, surficial geology, soils, surface water hydrology, water supplies, exploratory drilling for mineral resources, aggregate deposits or groundwater wells, forest resources, peat deposits, sand and gravel deposits, wetlands, vegetation, and wildlife of the Shield.

Useful information on the location and chemical character of groundwater discharge areas can be obtained from water quality data from domestic water supply wells or surface water bodies in the region. Gascoyne and Elliot (1986) used water quality information from domestic water supply wells contained in provincial government records to determine the relative amount of deep saline groundwater that might be discharging from the rock into the shallow groundwater regime at the Whiteshell Research Area.

Table 2-2 summarizes the types of information that are available and what they are used for initially in site screening.

Table 2-2. Compilation and Analysis of Pre-existing Information.

Type of Information	Use
Geological maps, reports, and mineral exploration records	- determine the geological setting, lithological distributions, and heterogeneity - identify geological structures such as major faults or fracture zones
Geophysical surveys and reports	- same as above
Soils and surficial geology maps and reports	- same as above - determine overburden distribution and characteristics
Seismic monitoring records	- determine rates of historical seismicity - estimate seismic hazard
Topographic, hydrologic and hydrogeologic maps, reports and records	- identify drainage basins and groundwater recharge and discharge areas - identify potential aquifers
Meteorologic data	- quantify potential for runoff, erosion, and groundwater recharge
Mineral exploration records and reports	- identify rock types, structural features, and potential mineral resources
Water resource surveys, including water well records	- determine shallow groundwater conditions, potential for water supplies, and groundwater and surface water chemistry
Forestry, wetlands, and biological distribution maps	- identify ecosystems, soil type variations, and groundwater recharge and discharge areas - estimate environmental sensitivity
Historical and archaeological maps and reports	- identify heritage and archaeological sites and lands requiring special consultation with aboriginal peoples
Administrative and service maps	- identify parks, forest preserves, communities, roads, railroads, pipelines, power lines, etc.

2.3.2 Compilation and Integration of Information

During site screening to identify potential candidate areas, the existing information would be integrated as it was compiled with a view to developing conceptual models of the domains (lithostructural, hydrogeological, etc.) for each potential candidate area. A conceptual model is a visual or schematic representation of the characteristics of the area or site, such as a map, cross-section, or block diagram. Even very simplified conceptual models would enhance communication with potential host communities and would provide a framework for the ongoing reconnaissance investigations.

One type of representation would be the output from a computer-based geographic information system (GIS). Using a GIS, the existing information and any siting criteria that had been established could be expressed geographically in map form showing areas that were excluded from consideration, that were potentially suitable, or that were otherwise ranked in some way. A GIS is particularly useful for a siting process involving continuing public participation, because it allows the geographic criteria and weighting factors to be changed easily and the results to be visually displayed as readily understandable maps. This would allow all participants in the screening process to compare the results of alternative choices of criteria and weighting factors as well as to compare the results for alternative areas or sites for a given set of criteria and weighting factors.

Integration of the available information into maps and tables showing those factors that relate to disposal system performance and safety would assist in the identification of potential candidate areas in the vicinity of potential host communities. The compiled information would provide the initial technical basis for interaction with potential host communities in the development of community-specific criteria for excluding or selecting candidate areas and sites and factors for ranking areas and sites. It would allow comparisons to be made between potential candidate areas in discussions with potential host communities.

2.4 RECONNAISSANCE INVESTIGATIONS

2.4.1 Introduction

Reconnaissance investigations would employ primarily traditional methods of field geology, mineral exploration, terrain analysis, and environmental analysis. However, the reconnaissance investigations during site evaluation at candidate areas would involve more detailed surface investigations than would the initial reconnaissance investigations during site screening within siting regions. The detailed surface investigations would include the following:

- systematic geologic mapping and sampling of lithology and structural fabric elements in outcrop, and mapping fractures in outcrop;

- careful examinations of topographic and geophysical lineaments to determine their geologic characteristics, particularly to assess if they are fracture zones;
- systematic airborne and land-based geophysical surveys to determine lithologic and structural variations;
- geophysical surveys to detect the existence of features such as fracture zones in the rock that reflect acoustic (seismic) waves or high frequency electromagnetic (radar) waves;
- surveys to record sonar reflections from the bottoms of lakes or rivers both to trace structural discontinuities beneath the water bodies which are evident on adjacent land as well as to determine the stratigraphy of the sediments deposited in the bottom of water bodies and examine them for evidence of postglacial faulting and groundwater discharge features;
- surveys of the physical and chemical characteristics of groundwater springs and seepages or other surface evidence of groundwater discharge;
- surveys of natural levels of helium and radon gases in soils and surface waters to help delineate groundwater recharge and discharge conditions;
- surveys of soils, flora and fauna to help identify and characterize groundwater discharge locations and to help evaluate the sensitivity of the surface environment to the potential effects of a repository;
- surveys to determine surface water catchment areas, lake areas and lake depths;
- surveys to establish sediment accumulation rates in water bodies and the thickness of mixed sediments; and
- developing monitoring networks for ongoing observations of meteorology, hydrology, vegetation, and animals (to establish the baseline surface environmental conditions, Davis et al. 1993).

The reconnaissance investigations at candidate areas would yield two particularly important types of geological information for the subsequent phases of site evaluation which involve subsurface investigations. First is the identification of features that may represent the surface expression of major pathways for groundwater flow in the rock. Of particular interest is the identification of features that might be large fracture zones and faults in the rock. Generally, these are major linear features observable on satellite images and aerial photographs or significant anomalies identified from the geophysical, hydrologic, or geochemical surveys. A second interest is the identification of other small-scale features in the rock that indicate the possibility that the properties of the rock controlling groundwater flow and geomechanical responses may vary with direction (anisotropy), for example, lithologic layering, textural or structural fabric, foliations, or fracturing and jointing.

AECL's research and development of site investigation methods has involved the application of some reconnaissance site evaluation methods at all of the Research Areas on the Canadian Shield. Early studies at the Chalk River

Research Area during 1977 to 1980 involved the development and use of numerous reconnaissance site evaluation methods (Thomas and Dixon 1989). However, the most extensive studies have been performed at the East Bull Lake, Atikokan, and Whiteshell Research Areas (McCrank et al. 1994, Stone et al. 1992, and Brown et al. 1994, respectively). The following sections discuss examples of reconnaissance investigations drawn mainly from the work done at these three major research areas.

2.4.2 Brief Field Investigations During Site Screening

Although site screening mainly involves the office compilation of existing information and data from the wide variety of sources described in Section 2.3.1, reconnaissance field investigations would also be carried out to verify the existing data, to obtain additional data, and to confirm or modify the office interpretations. These reconnaissance field investigations would be performed during site screening primarily by conducting ground checks of the interpretations initially developed from the compilation and integration of the existing information using access provided by existing roads or trails, boats, helicopters or float planes.

The initial field reconnaissance would involve brief (less than two weeks) visits to each of the potential candidate areas that had been identified in the siting regions. A small team of scientists would assess the following conditions:

- accessibility for mapping, geophysical surveys, drilling, and hydrological monitoring (roads, terrain, etc.);
- topographic relief and drainage, including surface water quality;
- soils, vegetation and wildlife;
- recharge or discharge of groundwater;
- distribution of outcrop and overburden, including outcrop density;
- lithologic properties (verification of existing maps and reports);
- fracture density at selected outcrops; and
- nature of previously identified lineaments.

The information obtained during these brief visits would be combined with a preliminary analysis of large scale faulting based on the lineament analysis, existing geophysical surveys, a delineation of hydrological drainage catchments, and an evaluation of environmental sensitivity to assess the suitability of each potential candidate area for conducting additional, more detailed reconnaissance investigations. Examples of such evaluations used in selecting AECL field research areas are Leech and Cooper (1982a, 1982b).

If there were a large number of potential candidate areas, some additional reconnaissance surveys might be needed to help rank the areas and select a small number for evaluation.

2.4.3 Lineament Analysis

Lineaments from Landsat TM would be identified by inspection on the computer screen, in cases where digital data were available. Where digital data were not available for computer assisted processing, as in the case of airphotos, the lineaments would be identified initially on the photographic image by visual inspection and then would be compiled in a lineament mosaic for subsequent digitizing and entry into a computer data base.

Then the lineament orientations, spatial frequency distributions, length distributions, geometric shape, and association with particular tectonic or lithologic terrains would be examined. If fracture frequency data were available from the reconnaissance mapping of outcrops, it would be compared with the lineament data to establish relationships (if any) between the fracture data and any of the lineaments or sets of lineaments. Then, lineaments of various sizes would be ranked as to their likelihood of being faults. Examples of this type of lineament analysis are contained in the reports by Brown et al. (1980), Brown et al. (1982), Brown and Rey (1982), McCrank et al. (1983), and McCrank (1985).

2.4.4 Geophysical Surveys

Most of the pre-existing geophysical survey information during site screening would be from airborne surveys flown at relatively wide line spacings (several hundred metres or more). During site evaluation, such surveys would be reflown at closer line spacings over the candidate areas and more detailed surveys would also be done on the ground, although generally not over the entire areas.

Magnetic, gravity, radiometric and electrical surveys all provide reconnaissance information that is useful for

- identifying and delineating individual plutons and different phases within plutonic rock bodies formed by multiple intrusions,
- assessing the homogeneity of rock bodies,
- determining the regional structural or geologic setting, and
- inferring the fracture characteristics of the rock bodies.

Because they are intruded as molten rock, plutons are usually more homogeneous than the country rock into which they intrude. They also have different lithologies, unless they intruded an earlier pluton from a similar magma. Consequently, a pluton will often have either a higher or lower magnetic mineral content than the country rock and will appear as an anomaly in the magnetic field in an aeromagnetic survey (Figure 2-2a). The aeromagnetic data can also be processed to produce vertical gradient maps which are useful in identifying the structure and lithology and in evaluating the homogeneity/heterogeneity of the pluton and its surroundings (Soonawala 1984, Gibb and Scott 1986, Soonawala et al. 1990). Higher or lower magnetic gradient values are sometimes aligned to produce magnetic lineaments that have orientations consistent with observed orientations of lithological variations or structural features in the rock such as fracture zones.

For the same reason that a pluton often has a different magnetic mineral content than the country rock, it also often has a different density, which can be observed as a gravity anomaly (Figure 2-2b). Consequently, maps of the regional gravity field (Bouguer gravity) are also useful in delineating the boundaries of plutonic rock bodies.

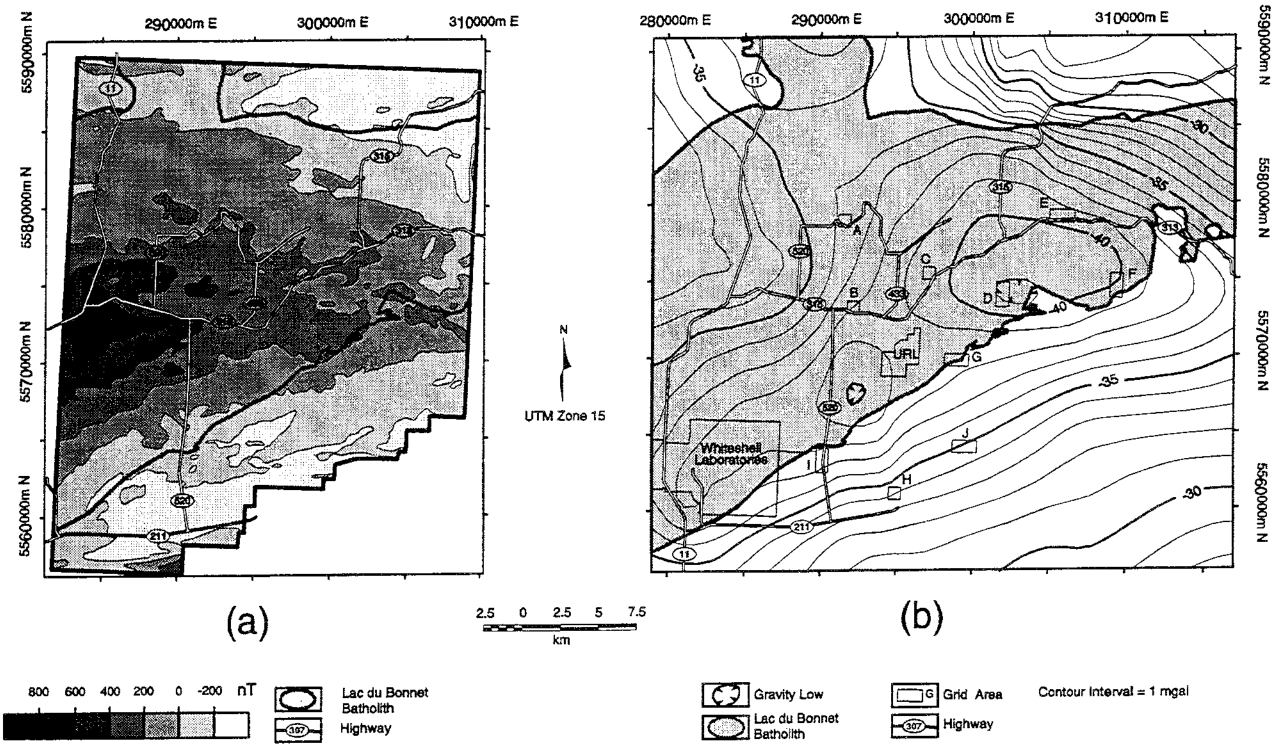

Figure 2-2. Magnetic (a) and Gravity (b) Fields, Whiteshell Research Area.

A combination of gravity and magnetic data and reconnaissance geological mapping of available outcrops can be used to develop a model of the shape and orientation of the boundaries of the plutons. Comparative modelling of gravity and magnetic data along selected section lines can provide information about the likely size, shape, and depth of plutons as well as about the lithologic characteristics of the surrounding country rock. Of particular importance is the subsurface orientation of the contacts between the pluton and the surrounding rocks which can be inferred from these surveys. Figure 2-3 shows an example of a 2-D lithologic model of the Whiteshell Research Area which was produced from an analysis of the airborne magnetic survey and gravity data collected from surface surveys.

Electrical survey methods are widely used to determine features of the surface and subsurface geology by measuring variations in the electrical conductance of the ground. In Shield terrain such variations can be caused by changes in the thickness and lithology of overburden materials, fractures in the rock (vertical or dipping), mineralization, and changes in the salinity of the water saturating the small pores and cracks in the rock matrix. A variety of reconnaissance electrical methods can be used to investigate the subsurface geology of Shield terrains to depths ranging from a few metres to a few kilometres (Gibb and Scott 1986, Soonawala and Hayles 1986, Soonawala et al. 1990). These include

- airborne surveys in the electromagnetic (EM) energy range (1,000 to 32,000 Hz) using multifrequency coaxial/coplaner coils.
- airborne surveys using radar energy.
- airborne surveys at very low frequency (VLF) energy (~24 kHz) to measure the response to signals generated by remote naval communications transmitter stations.
- audiomagneto-telluric (AMT) and magneto-telluric (MT) methods for intermediate to deep investigations.

Data from airborne VLF-EM and multicoil-multifrequency EM surveys can be very useful in mapping the distribution and thickness of unconsolidated deposits of overburden covering Shield terrains. Although these surveys would certainly be carried out at candidate areas during the early part of site evaluation, some airborne survey data could already be available for some areas and used during site screening.

Ground EM surveys involving multifrequency horizontal loop systems like Geonics EM-36, MAX-MIN, and Schlumberger soundings can differentiate sediment layering within the overburden deposits (Soonawala 1984) if there are significant variations in soil structure, clay content, salinity of the soil water, or the degree of water saturation in the soil.

The ability of the reconnaissance electrical survey methods to detect fractures or fracture zones in the rocks depends upon the thickness of the fractures, the electrical conductivity contrast that exists between the fractures and surrounding rock, the length and areal dimensions of the fractures, the amount of overburden, and the type of electrical method used.

Deep penetrating electrical survey methods such as time domain EM (TDEM), controlled source audio magneto-telluric methods (CSAMT) and magneto-telluric (MT) methods have the potential to trace some vertical and low-dip fracture zones in granitic rock over a depth range of 100 m to 10 km (Gibb and Scott 1986). The lower the frequency of the transmitted waveform in the survey the deeper the survey can penetrate. However, for a fracture zone to be detected, the conductivity-thickness product of the zone has to be at least 10% of the conductivity-thickness product of the overlying rock mass.

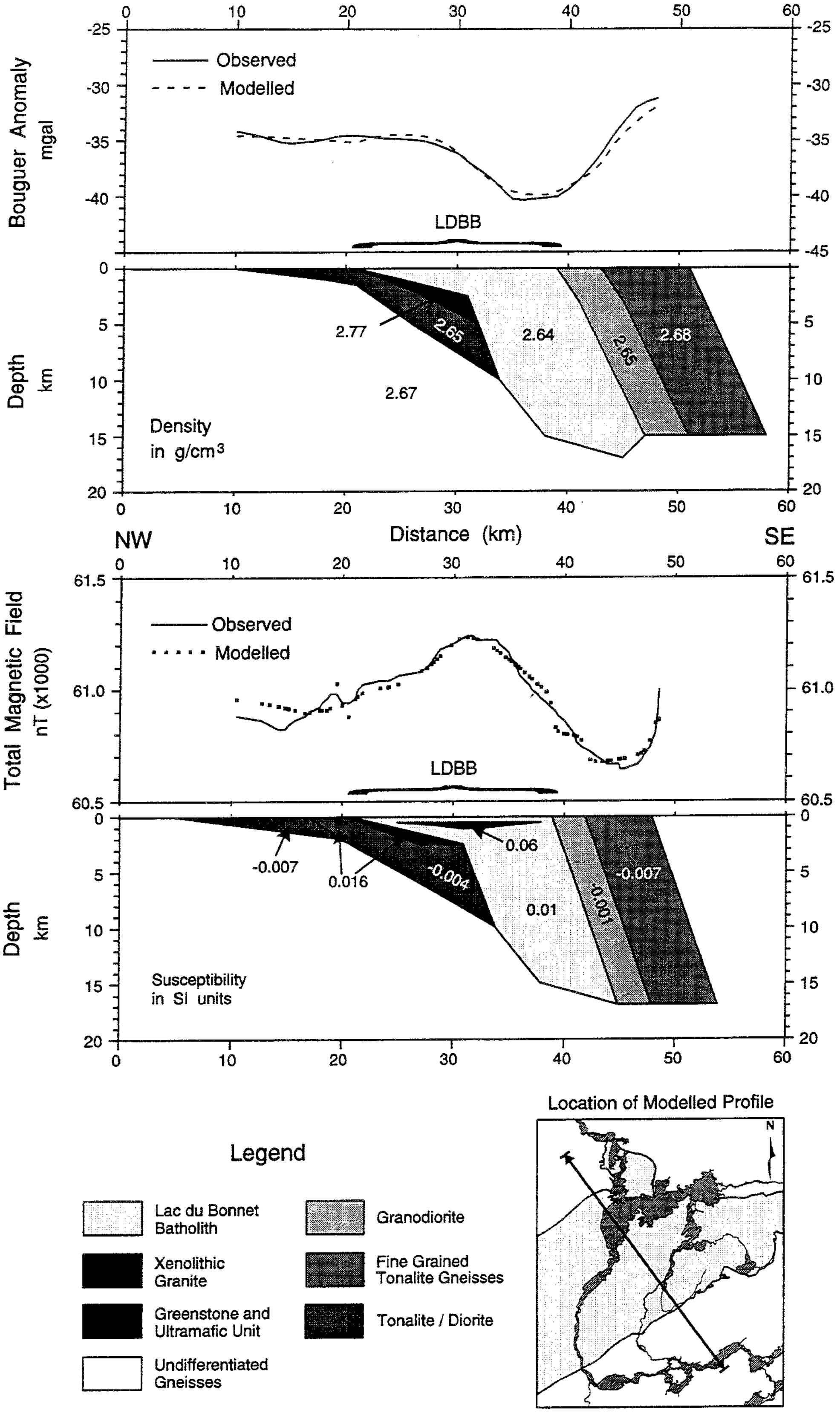

Figure 2-3. Magnetic and Gravity Models, Whiteshell Research Area.

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AECL has used dipole-dipole resistivity, CSAMT, AMT and MT surveys at the Whiteshell and Atikokan Research Areas. However, the interpretation of the results with respect to the location of major fractures zones and variations in lithology and geologic structure remains inconclusive because no boreholes have been drilled deep enough at these research areas to determine the nature of the features inferred from the survey data.

Surface radar surveys can detect reflections from low-dip fracture zones to a depth of up to 80 metres below outcrop depending on the survey frequency (Holloway et al. 1992, Stevens et al. 1994). Sparsely fractured or moderately fractured granite is much more electrically resistive than the fracture zones so radar pulses are reflected from water-filled fracture zones. Reflections may also be generated from changes in lithology or from boreholes or excavations in the rock (Andersson et al. 1987, Olsson et al. 1987, Soonawala et al. 1990, and Holloway et al. 1992). Radar systems for geotechnical applications operate within a frequency band from about 10 to 1000 MHz. Higher survey frequencies result in greater resolution but shallower probing distances. Consequently high frequency surveys are of more use for mapping fractures in the near field surrounding underground excavations than for surface surveys.

Sonar profile surveys of lake bottoms can be useful for determining the topography of the underlying bedrock surface and for investigating the stratigraphy of the sediments infilling the lake bottoms. AECL used this method to prepare a map of the bedrock topography beneath Eye Lake at the Atikokan Research Area (Figure 2-4). The linear features on the lake bottom align with lineaments on land which have been identified from airphotographs and topographic maps (Holloway 1985).

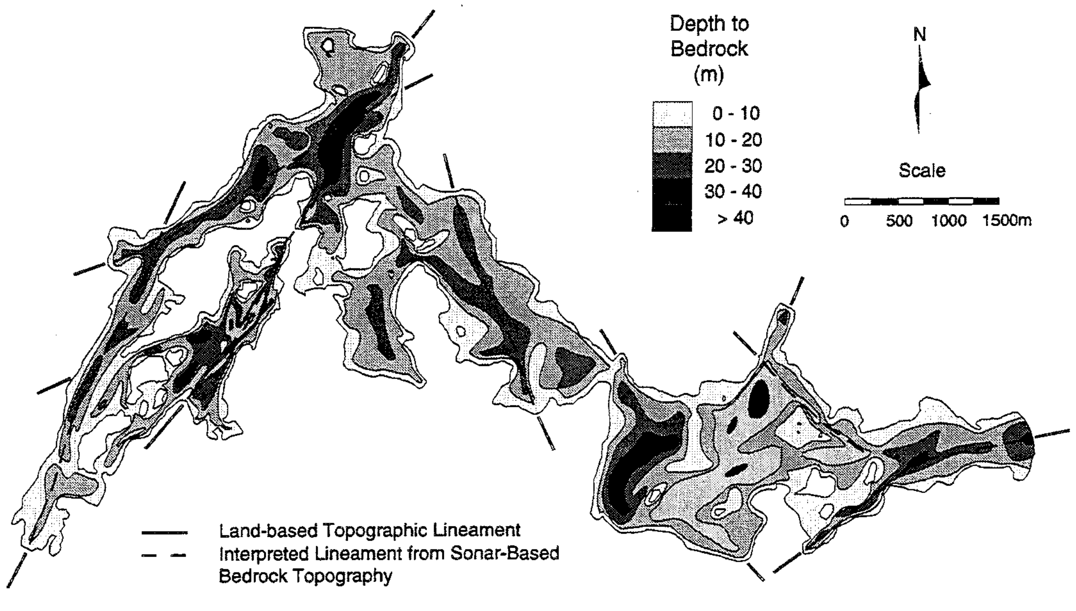


Figure 2-4. Lake Bottom Topography of Eye Lake.

High resolution, high frequency seismic reflection surveys can generate observable reflections from low-to-intermediate dip fracture zones in plutonic rocks from depths of 100 m to depths of 2000 m or greater (Soonawala et al.

1990). However, variations in fracture zone thickness may produce discontinuous reflections that make the identification inconclusive. At an average high frequency seismic signal of 100 Hz, the quarter wavelength of a seismic wave in granite (velocity 6000 m/s) is 15 m. This implies that portions of fracture zones thinner than 15 m in the rock are unlikely to be detected as continuous seismic reflectors. Significant research on applications of high resolution seismic surveys for mapping deep lithological and structural changes in rocks of the Canadian Shield is currently being done under the national Lithoprobe program (Clowes et al. 1992). This may lead to improvements in the method.

Granitic rocks are generally enriched in the naturally occurring radioelements uranium, thorium, and potassium. Therefore granitic plutonic rock bodies often can be identified on maps or profiles compiled from airborne radiometric surveys. The national uranium reconnaissance program, carried out by the Geological Survey of Canada during the 1970's provides an excellent data base for the construction of regional radiometric maps or profiles for the Canadian Shield.

2.4.5 Geological Mapping

The geological mapping that would be performed during site evaluation would likely be done at one of the common scales of existing aerial photographs (approximately 1:16 000). Within a candidate area all outcrops (or grouped outcrops) over 2500 m^2 in size would be inspected and mapped. In the surrounding region, depending on stratigraphic and structural complexity, geologic mapping would be done along traverses spaced from 0.5 km to 2 km apart, for whatever portion of the region was needed to provide the regional geologic setting for the candidate area. For instance, the geologic map of the Atikokan Research Area covered 1120 km^2 surrounding the 80 km^2 Eye-Dashwa Lakes Pluton (Stone et al. 1992). At the Whiteshell Research Area, the regional scale geological mapping has covered more than 3500 km^2 surrounding the 700 km^2 research area.

Commonly, the geologic data collected during reconnaissance surveys at the regional scale is recorded on transparent plastic sheets overlying the photographs for the traverses in the region. Quantitative information collected during reconnaissance surveys in the candidate area is recorded on overlays and coding sheets. Mapping data are compiled at the field scale of 1:16 000 and later reduced to 1:50 000 in the office.

The types of geologic data that would be recorded during the reconnaissance mapping done at the regional scale are summarized in Table 2-3. The mapping done on outcrops within the candidate area would involve the collection of similar data but would be considerably more detailed than that done on the outcrops outside the candidate area.

Table 2-3. Geologic Data From Reconnaissance Mapping of Candidate Areas.

Type of Data	Use
Percentage of rock type and spatial distribution of large rock units	Determine geometry of major units, folding, style of contact between major units, and degree of granitization.
Lineament analysis	Identification of faults, fracture zones, and areas without major discontinuities.
Fracture density	Relationships to rock type or proximity to faults or fracture zones.
Fracture orientation, length, and infilling material	History of fracturing and orientation of stress field, geometry of faults and fracture zones.
Rock and fracture infill samples	Identification of pressure/temperature (P/T) conditions during pluton emplacement and during episodes of fracturing, dating of episodes of deformation, determining cooling rates of plutons, and determining chemical and mineralogical composition.

The mineral composition of the various intrusive phases of the plutonic rock bodies would be estimated and rock samples would be taken from the outcrops for laboratory analyses of lithology, mineralogy, fracturing, fabric and isotopic age (Section 2.4.8).

The surface topography would be examined for signs of fault locations especially adjacent to major topographic or geophysical lineaments (e.g. the cliff-and-dip slope of near surface thrust faulting, Stone and Kamineni 1988).

The outcrops would also be examined for deformation evidence, such as foliation fabrics and fracture kinematic features. Such evidence can be very useful in establishing if the primary fabric had any control in the later development of fault or fracture zones. Crosscutting relations would be examined to establish the relative chronology of lithology, fabric and structural features. Obvious fold data would also be measured. Within the candidate areas, line samples would be used to map mesoscopic fracture intensity and the fracture characteristics such as length, aperture and infillings would be recorded.

2.4.6 Hydrological Investigations

The initial hydrological investigations would focus on the major watersheds and tributary catchments to develop an overall assessment of the hydrologic conditions of the region. This would include an evaluation of surface water flows, surface water level fluctuations and accessibility of potential sites for longer term routine monitoring. Particular attention would be given to assessing general field conditions and determining the methodology, instrumentation and equipment that would be required for any subsequent detailed investigations.

Later, hydrologic monitoring stations would be installed to investigate the relationships between precipitation, streamflow, wetland storage, and groundwater recharge and discharge. Long-term studies of the patterns and distributions of precipitation and surface water runoff in several small catchments at the Whiteshell Research Area have been used to estimate the interrelationships between precipitation, surface water runoff, groundwater recharge, and groundwater discharge in Shield terrains (Thorne 1990a, Thorne et al. 1992, Thorne and Gascoyne 1993).

Reconnaissance surveys of the spatial and temporal variations in the ionic content of the surface waters would be done in the candidate areas. Methods that have proven useful for identifying locations of groundwater discharge include measurements of Cl^- and other ions in surface waters (Thorne 1986), mapping variations in the electrical conductance or temperature of surface waters using a lake- or river-bottom drag probe (Lee 1985, Lee et al. 1993), and using airborne or satellite thermal infrared imagery to detect anomalous patterns in the temperature of surface waters (Lee and Tracey 1984). Chemical analysis of surface water samples can also be used to determine baseline concentrations of naturally occurring radionuclides (Larocque and Gascoyne 1986).

2.4.7 Hydrogeologic Investigations

Surficial geological deposits and outcrop would be examined for hydrogeological features to obtain an initial conceptual idea of groundwater movement within the candidate region. An evaluation of surface indicators of groundwater discharge (springs and seeps) can provide useful information about the storage and permeability of the surficial deposits or rock. Estimates of discharge rates and measurements of the water chemistry of springs and seeps can provide useful information to assist in an initial hydrogeologic assessment.

Localized occurrences of anomalously high levels of dissolved salts in surface waters and soils are known to attract animals such as deer and moose. Some examples of these occurrences on the Shield (known as 'moose licks') have been studied in the Nipigon area of northwestern Ontario and are reported to be caused by the discharge of saline groundwater (Frape et al. 1984). Recent investigations at the Whiteshell Research Area have shown that elevated levels of chloride occur in shallow groundwaters and nearby surface waters in areas where groundwaters from deep saline flow systems discharge at surface. In some places these correspond to areas that attract deer for feeding (Gascoyne et al. 1993).

Analysis of the content of the dissolved gases radon and helium in the soils and surface waters would be done in locations where discharge of deep groundwater was suspected. This method (Gregory and Durrance 1987) has been used successfully at the Whiteshell Research Area, where anomalies in radon and particularly helium have been identified in the soils and surface waters over an area where groundwaters from deeper, large scale flow systems discharge to surface through a large fracture zone (Gascoyne and Wuschke 1990, Stephenson et al. 1992). In one location a helium anomaly has been found associated with a small deer lick. A thorough analysis has shown elevated levels of chloride in the shallow groundwaters beneath the location, suggesting that this is likely a discharge area for groundwater from a deep, helium-rich saline flow system (Gascoyne et al. 1993). A similar technique to measure the buildup of helium gas in surface waters during periods of winter ice cover has also proven to be useful in identifying locations at which groundwaters from deeper flow systems discharge into surface waters (Stephenson et al. 1993).

2.4.8 Laboratory Analysis of Rock Specimens

Laboratory methods to examine the rock specimens collected during regional geological mapping would include

- thin section optical microscopy,
- scanning electron microscopy,
- bulk rock and specific mineral chemical analyses of major and minor elements (in whole rock and in fracture infillings), and
- radiometric dating of primary and secondary minerals.

Such laboratory studies are designed to develop an understanding of the geological environment that existed during initial intrusion and crystallization of the plutonic rock bodies and to establish the history of any subsequent ductile and brittle deformations that may have occurred. Feldspar geothermometry is also used to study the relative ages of fault zone formation (Kerrich and Kamineni 1988).

Trace element analyses provide information for the development of petrogenetic models. In particular, studies of the distribution of natural U, Th, and rare-earth elements in the rock and fracture filling minerals provide insight into processes that affect radionuclide migration or retardation in the rock. Laboratory examination of rock samples from both the Lac du Bonnet Batholith and the Eye-Dashwa Lakes Pluton shows that these elements were mobilized during periods of rock alteration early in the emplacement history of both plutons. However, these elements became reconcentrated in some fault zones through selective sorption and precipitation in minerals such as uraninite, bastnaesite, thorite and thorogummite (Kamineni 1986).

Radiogenic isotope studies also help establish the age of pluton formation, the cooling rate of the pluton and the subsequent ages of fracturing, faulting and associated alteration events (Peterman and Kamineni 1990).

2.4.9 Summary of Reconnaissance Methods

Table 2-4 summarizes the reconnaissance methods for site investigations. These methods would provide the information needed to identify potentially suitable candidate areas for a repository and within a candidate area to identify locations for grid areas for detailed investigations. How the information provided by the methods would be used is also summarized.

Table 2-4. Reconnaissance Investigation Methods.

Method	Type of Information	Use
Airphoto and Satellite Image Analysis	- black and white, colour, and thermal infra-red photographs and satellite images	- determine rock outcrop and rock types - identify lineaments - identify vegetation patterns and potential groundwater discharge locations
Analysis of Topographic Maps	- topographic maps	- determine local and regional topographic variations - identify drainage basins and structural controls on drainage patterns - identify springs
Geophysical Surveys	- aeromagnetic total field and magnetic field gradient	- identify pluton boundaries and depths and structural style of area - identify lineaments
	- airborne electromagnetic and very low freguency electromagnetic field	- estimate lithologic variation and overburden distribution and thickness - identify lineaments
	- airborne radiometric field	- identify pluton boundaries and lithologic variations
	- airborne and surface gravity	- identify pluton boundaries and depths
	- airborne and surface radar	- identify lineaments - identify fracture zones in shallow subsurface
	- surface reflection seismic	- identify fracture zones in subsurface
Geological Mapping	- lithology at outcrops	- verify and refine existing geological maps
	- fracture distribution, frequency, and orientation at outcrops	- determine fracture history - determine location, extent, and orientation of major faults and fracture zones
	- petrography of rock samples and fracture infillings	- develop tectonic history of plutonic rock in the region

Table 2-4. Reconnaissance Investigation Methods (continued).

Method	Type of Information	Use
Hydrological and Hydrogeological Surveys	- drainage patterns and streamflow and water level fluctuations	- define drainage basins, range of runoff volumes, ratio of local to regional flow
	- characteristics of springs, outcrops, and surficial deposits	- assess groundwater recharge and discharge relationships
	- water use	- assess resource requirements - identify major aquifers
Geochemical Surveys	- chemistry of surface water	- estimate runoff and groundwater discharge relationships - establish initial baseline conditions
	- chemistry of springs and groundwater from water wells	- estimate relationship between deep and shallow groundwater flow systems - establish initial baseline conditions
	- chemistry of soil gas	- identify terrestrial discharge from deep groundwater flow systems - establish initial baseline conditions
	- electrical conductance of bottom sediments and bottom waters in lakes and rivers	- locate subaqueous discharge of groundwater - establish initial baseline conditions
	- chemistry of lake bottom gas discharges	- same as above
Biological Surveys	- plant and animal inventories	- confirm existing maps - identify ecosystems, unique communities, and sensitive species - establish initial baseline conditions
Cultural History Survey	- cultural inventory	- identify heritage sites - identify aboriginal burial grounds - identify archaeological sites

2.5 DETAILED INVESTIGATIONS AT SURFACE AND IN BOREHOLES

2.5.1 Use of Grid Areas for Detailed Investigations

The initial objective of site investigations at grid areas would be to identify a location (candidate site) within the candidate area that appears to be technically suitable for a repository, or alternatively to establish that the area should no longer be considered a candidate for a repository.

The reconnaissance investigations would have identified features within the candidate area that might represent major pathways for groundwater flow and features that might indicate possible anisotropy in the properties of the rock controlling groundwater flow or geomechanical responses.

Numerous small study areas (grid areas) would be selected at various locations within or near the candidate area for detailed investigations to establish correlations between the inferences drawn from satellite, airborne and surface investigations and what exists in the subsurface. The main emphasis of these geotechnical investigations would be to obtain subsurface information which would be integrated with surface information to provide a three-dimensional representation of the physical and chemical characteristics of the candidate area. This representation would provide the basis for developing a three-dimensional understanding of the hydrogeological and geomechanical conditions within the candidate area (Chapter 3).

In parallel with the geotechnical investigations at the grid areas, environmental investigations would be conducted to improve the understanding of the baseline conditions in the natural environment by obtaining more detailed information on the plants, animals, hydrology, soil, and atmospheric conditions at the candidate area.

The geotechnical information would be used to develop a conceptual model of the features of the candidate area important for groundwater flow and contaminant movement. Based on this conceptual model, the information would also be used to develop and calibrate a three-dimensional mathematical model of regional groundwater flow. This model would be used to evaluate potential locations of discharge of contaminants based on alternative locations for a repository within the candidate area.

Based on the results of the evaluation, simplified models would be developed of contaminant movement to the surface from a repository at each of the alternative locations. These geosphere models (Chapter 3) combined with models of contaminant movement in the surface environment and through the food chain (biosphere models) would be used to help select the preferred location for a repository within the candidate area. The candidate site would comprise an area of about 25 km^2 encompassing the preferred location for a repository.

Subsequent investigations would then be designed for the candidate site. These investigations would be used to identify locations for exploratory shafts and underground tunnels, to obtain a much more thorough understanding of the particular conditions at the site, to develop engineering designs of the disposal system, taking proper account of local site-specific conditions and to conduct very thorough assessments of the potential environmental effects and long-term safety of alternative disposal system designs at the site. Investigations in exploratory shafts and tunnels are outside the scope of this report. Everitt et al. (1994) discuss AECL's approach to such investigations.

In addition to the investigations at grid areas, detailed investigations would also be carried out at other specific locations within the candidate area to obtain geological data on specific structural or lithologic features. For instance, any large outcrops, quarries or road cuts in the regional study area would be mapped in detail to provide geologic data along horizontal and vertical exposures.

Figure 2-5 shows the locations of the grid areas and other study areas at the Whiteshell Research Area, which illustrates this approach to characterization of candidate areas.

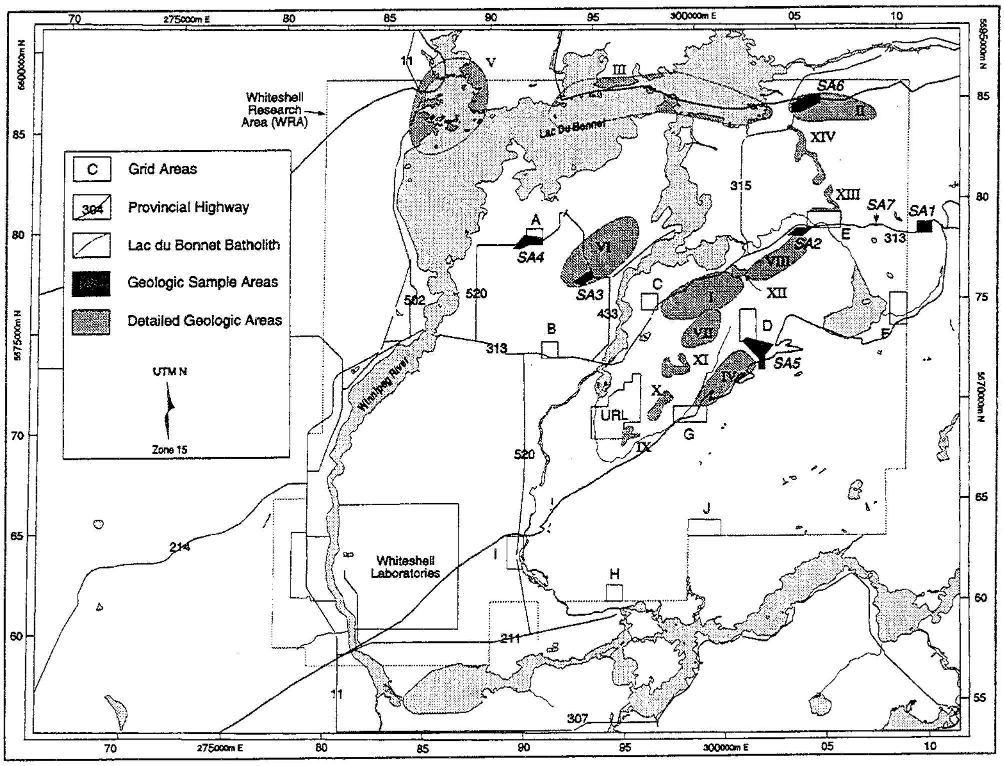


Figure 2-5. Location of Grid Areas at Whiteshell Research Area.

These supplementary detailed investigations would usually have very specific objectives. In the regional geologic investigations of the Whiteshell Research Area, small areas of outcrop lying along the main lithologic contacts and also in the centre of the batholith were selected and mapped in detail to determine whether the style of deformation mapped at the 4.8 km^2 URL lease area was representative of the entire batholith, an area of about 700 km^2. Foliations, fold geometry, dykes, ductile fault zones, fracture infillings and kinematic indicators were recorded at each outcrop (Brown et al. 1985).

Table 2-5 lists the types of geologic data that would be collected by surface mapping at grid areas and special geologic study areas and summarizes their use.

Table 2-5. Geologic Data from Grid Areas and Special Geologic Study Areas.

Type of Data	Use
Distribution and characteristics of rock types, large-scale fabric, xenoliths, foliations, and schlieren	- determine the geometry of the plutonic rock bodies - determine the emplacement and cooling history - determine the heterogeneity and anisotropy - determine effects on rock property tests and measurements - determine the factors controlling location, orientation, and density of fracturing - determine the deformation and stress history
Characteristics of faults, fractures, dykes, veins, and microcracks	- determine geometry of faults and fractures - determine current stress orientation - determine deformation and stress history - determine pressure/temperature conditions during emplacement and cooling - determine anisotropy of rock material behavior
Results from laboratory examinations and tests of rock specimens	- date deformation events and establish cooling rates - determine pressure/temperature conditions during emplacement and cooling - determine pressure/temperature conditions during episodes of fracturing - determine current stress orientation - determine deformation and stress history

At the Whiteshell and Atikokan Research Areas fractures in horizontal and vertical exposures were mapped in detail to determine the relationships between sets of fractures with various dips (Brown et al. 1994, Stone et al. 1994).

In many instances it is helpful to increase or improve the natural exposure of the rock or its structural features (fault zones, dykes etc.) at the grid areas by washing off a thin veneer of soil cover or excavating shallow trenches through soil-filled lineaments (McCrank et al. 1985, Stone 1985, Stone et al. 1989). In general, clearing allows better geological and geophysical information to be obtained which, in turn, aids in predicting the subsurface conditions beneath the grid area.

At the East Bull Lake Research Area a study was carried out by clearing and washing an area across the Folson Lake Fault to allow detailed mapping to be done at a scale of 1:10. This detailed mapping gave a clear understanding of the physical and chemical nature of the fault zone which could be related to its hydrogeological properties (McCrank et al. 1985). Similar studies of cleared outcrops or in trenches excavated to expose fault zones were used to establish fracture relationships at the Atikokan and Whiteshell Research Areas (Stone 1985, Stone et al. 1989). Excavations which expose the subsurface conditions of the various soils and other overburden deposits also enable detailed observations to be made of the geologic and hydrogeologic properties of these materials (Betcher 1983, Ridgway 1985).

In addition to correlations between surface and shallow subsurface conditions, studies at grid areas or special study areas provide specific information about important surface hydrologic and meteorologic processes that affect how groundwater moves through the rocks and soils at the site. Such investigations at Whiteshell Research Area included soil moisture flux studies, evapotranspiration studies, and special studies of groundwater recharge and groundwater discharge areas to characterize the quantity and distribution of groundwater movement (Thorne 1992).

Radar reflection surveys are used at the grid areas to probe the rockmass for electrical discontinuities. In granitic rocks reflections caused by water-filled fracture zones can be observed up to a depth of 80 metres under exposed outcrops using radar reflection surveys (Holloway et al. 1992).

Radar surveys on outcrop were used at the Whiteshell Research Area to establish the dip direction and continuity of low-dip fracture zones associated with topographic lineaments (Holloway and Mugford 1990, Holloway et al. 1992). This is particularly useful when selecting locations for investigation boreholes at grid areas (Holloway et al. 1992, Stevens et al. 1994).

Figure 2-6 shows a radar profile near borehole M-10 at the URL. There is excellent agreement between the location of the top of Fracture Zone 2 in the borehole and the reflectors in the radar data.

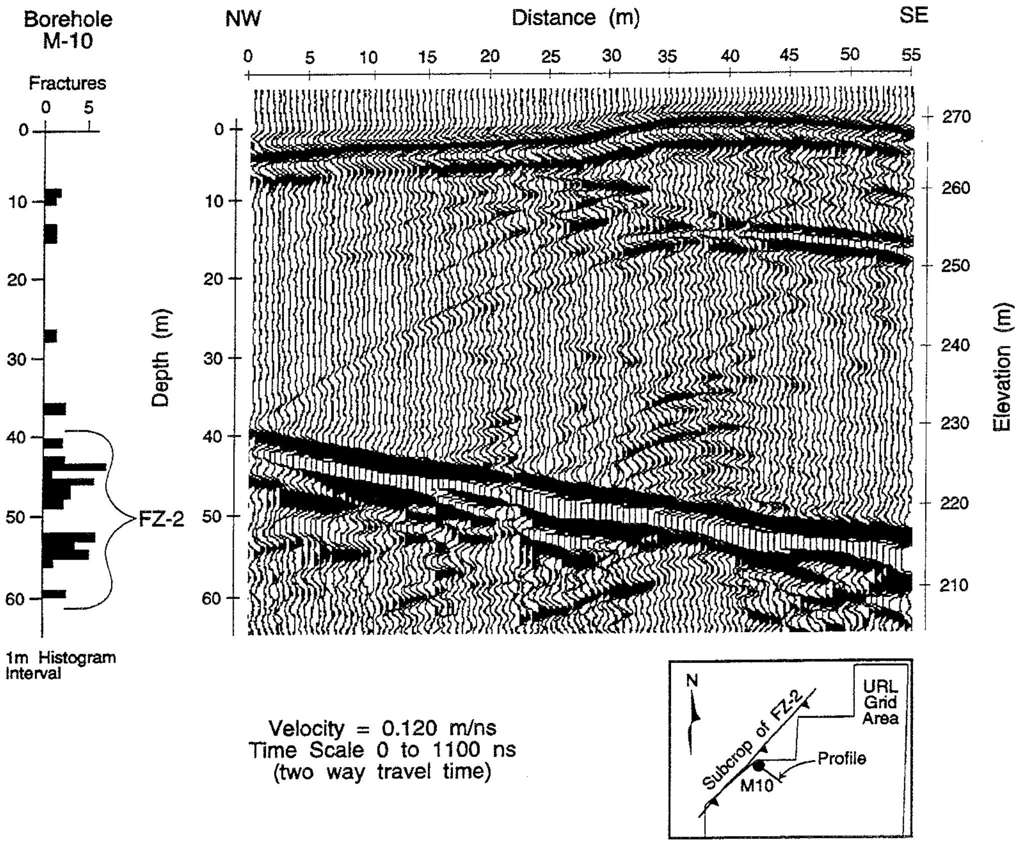


Figure 2-6. Fracture Zones in Surface Radar Data.

Borehole investigations would be essential for acquiring subsurface information from the grid areas. Boreholes would be drilled into both the overburden and the rock at grid areas to provide information about particular geological, geophysical or hydrogeological features that appear to be important at the regional scale. In some cases the grid areas would be chosen to examine the subsurface character of major lithologic contacts or surface lineaments that appear to be important regional fracture zones. At the Whiteshell and East Bull Lake Research Areas most of the grid areas were located to examine these types of regional features. Other grid areas would be chosen to investigate the subsurface conditions at locations that appear to be intrablock areas between major faults or that are away from major lithologic contacts. One of the grid areas at the Atikokan Research Area was selected to examine such an intrablock area on the Eye Dashwa Pluton (Brown and Rey 1985, Brown and Rey 1986).

The number of boreholes that would be needed at individual grid areas and within the candidate area as a whole would depend on the geologic complexity of each candidate area and on the ability to predict the geologic structure of the subsurface at the grid areas from airborne and surface measurements and from measurements made from within and between boreholes. AECL drilled sixteen boreholes to depths ranging from 400 to 1200 m at seven grid areas at the Whiteshell Research Area.

The scale of the site investigations at the Whiteshell Research Area is similar to what would likely be required for a regional evaluation of a candidate area for siting an actual repository in Canada. However, the layout of the grid areas and the distribution of the deep boreholes at the Whiteshell Research Area were not designed to locate a suitable site for disposal, but rather to expand the detailed investigations at the Underground Research Laboratory to the regional scale and determine the setting of the URL in the context of the regional groundwater regime. The locations of the grid areas were limited to land owned by the Province of Manitoba, consequently, some features of interest could not be investigated. However, the investigations at the grid areas illustrate AECL's approach to evaluating candidate areas for siting a repository.

The methods AECL has used for the drilling, logging, instrumentation, testing and sampling of shallow boreholes drilled into the overburden materials have been adapted from well established procedures for characterizing the geology and hydrogeology of unconsolidated materials and will not be elaborated upon here (Betcher 1983, Ridgway 1985, Thorne 1990b, and Thorne 1992). However, the methods for the drilling, logging, instrumentation, testing and sampling of deep boreholes drilled into the rock were not previously well established. These have evolved during the research and development programs at the research areas since 1977. The borehole methods AECL uses for characterizing subsurface conditions of plutonic rocks of the Canadian Shield are discussed below.

2.5.2 Investigations in Single Boreholes

2.5.2.1 Deep Borehole Drilling

The initial deep boreholes for regional scale site evaluation are drilled in a manner that allows a continuous sample of the rock to be collected. AECL has adapted the diamond core drilling methods commonly used in Canada for hard rock mineral exploration and mining applications. The boreholes are drilled using triple-tube, wireline core recovery methods. AECL usually drills 76 mm diameter boreholes (NQ size), although larger 96 mm diameter (HQ size) boreholes have been drilled when in situ rock stress measurements were to be made in the boreholes.

AECL does not allow the use of oils, muds or other additives as lubricants for the diamond drilling. Only clean water from nearby surface ponds or streams is used for cooling and flushing. Contamination of the groundwater by the drilling water is usually identified by using naturally-occurring tritium (^3H) or other chemical constituents in the surface water as tracers. Alternatively, a non-toxic dye tracer is sometimes added to the drill water. Use of natural tracers avoids the necessity of monitoring tracer injection and the problem posed by retardation of dye tracers on fracture-filling minerals. Ross and Gascoyne (1993a) describe techniques for distinguishing drill water from the groundwater.

AECL attempts to orient all core from boreholes. A gravity-based method of core orientation has been most reliable. Consequently, the boreholes drilled from surface are ususally inclined, commonly with a 75° plunge from horizontal. However, flatter inclinations are used when the lithologic and structural targets are expected to have near vertical orientations in the subsurface.

The orientation of each length of core with respect to the inclination of the borehole is recorded during the drilling. As soon as the core is recovered, a detailed description (core log) is made of the location, orientation, and character of fractures and a range of other structural and lithological features. Any evidence of high in situ stresses, such as core discing, is also recorded.

Percussion-drilled boreholes of 152 to 158 mm diameter are also used for the installation of standpipe piezometer systems to monitor hydraulic head, commonly to depths of less than 150 m, although AECL has used them to depths of 400 m. Percussion-drilled boreholes are used in situations where core is not needed and only a few monitoring intervals need to be isolated.

Gyroscopic surveys are done in boreholes immediately after the drilling is completed to determine the final orientation for the full length of the borehole. The gyroscopic survey data are used to translate the core orientation information into true spatial coordinates. Figure 2-7 is a summary geologic core log of a borehole illustrating the type of information recorded routinely during core logging. Figure 2-8 shows some of the presentation formats for fracture location, orientation and infill data.

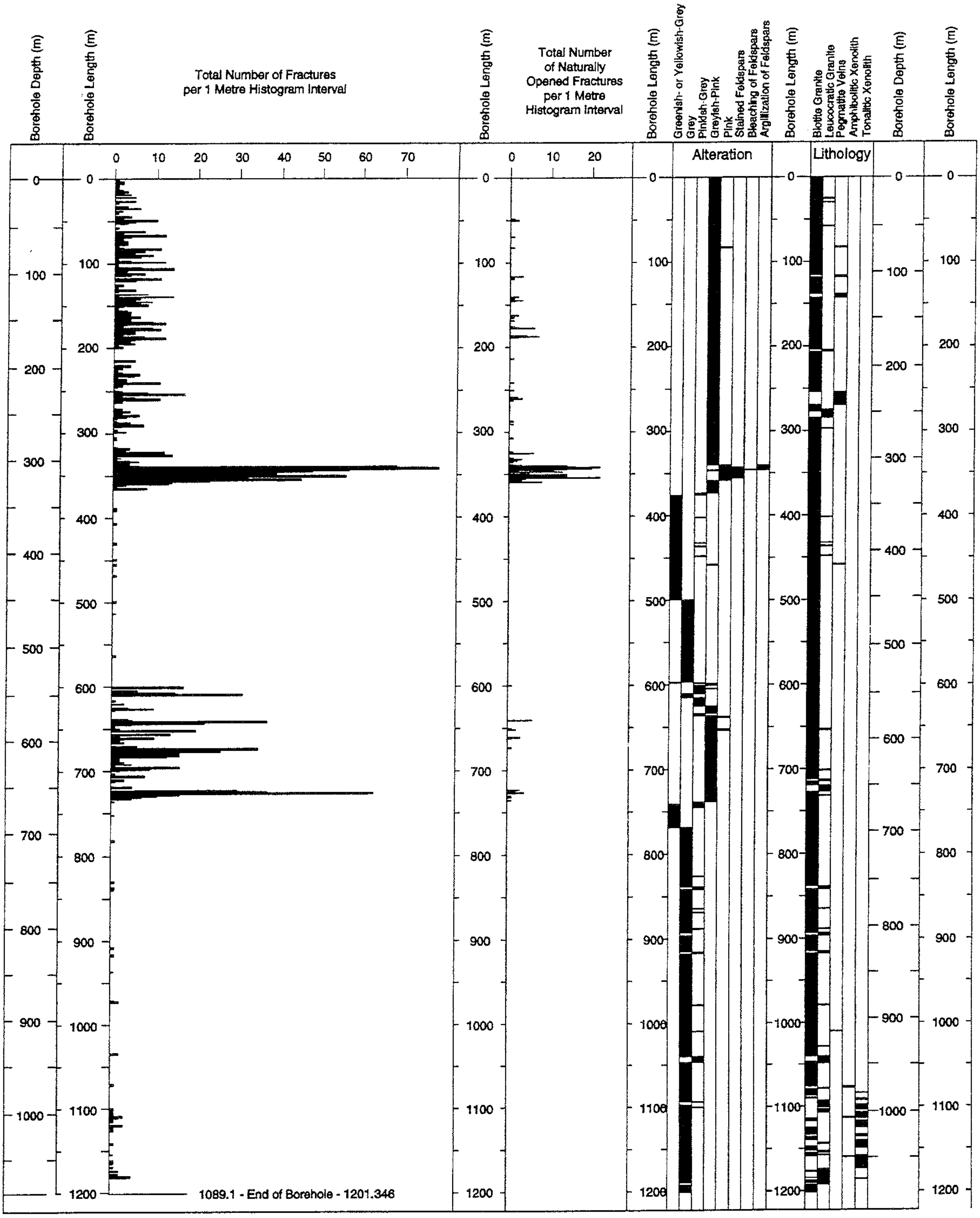


Figure 2-7. Summary Core Log.

Samples of the borehole core are selected for laboratory examination and testing to determine porosity and pore structure properties (including examination of microcracks), permeability, diffusion coefficient, strength (compressive and tensile), elastic modulus, Poisson's ratio, compressive wave velocity, magnetic susceptibility and anisotropy, and thermal conductivity and diffusivity (Soonawala et al. 1982). The testing includes an evaluation of the effects of confining pressure on the results.

Other core samples are selected for petrologic and geochemical study. Of particular interest are the changes in chemistry of the altered rock adjacent to and within fracture zones where there has been an interaction between flowing groundwater and the rock (Kamineni and Dugal 1982, Kamineni and Stone 1983, Griffault et al. 1993). Samples of minerals that have been exposed to groundwater in permeable zones or on the surfaces of open fractures are collected and studied in the laboratory to determine if they would interact to retard the movement of contaminants from nuclear fuel waste (Kamineni et al. 1982, Vandergraaf 1982, Kamineni and Lemire 1991, Vandergraaf and Ticknor 1993).

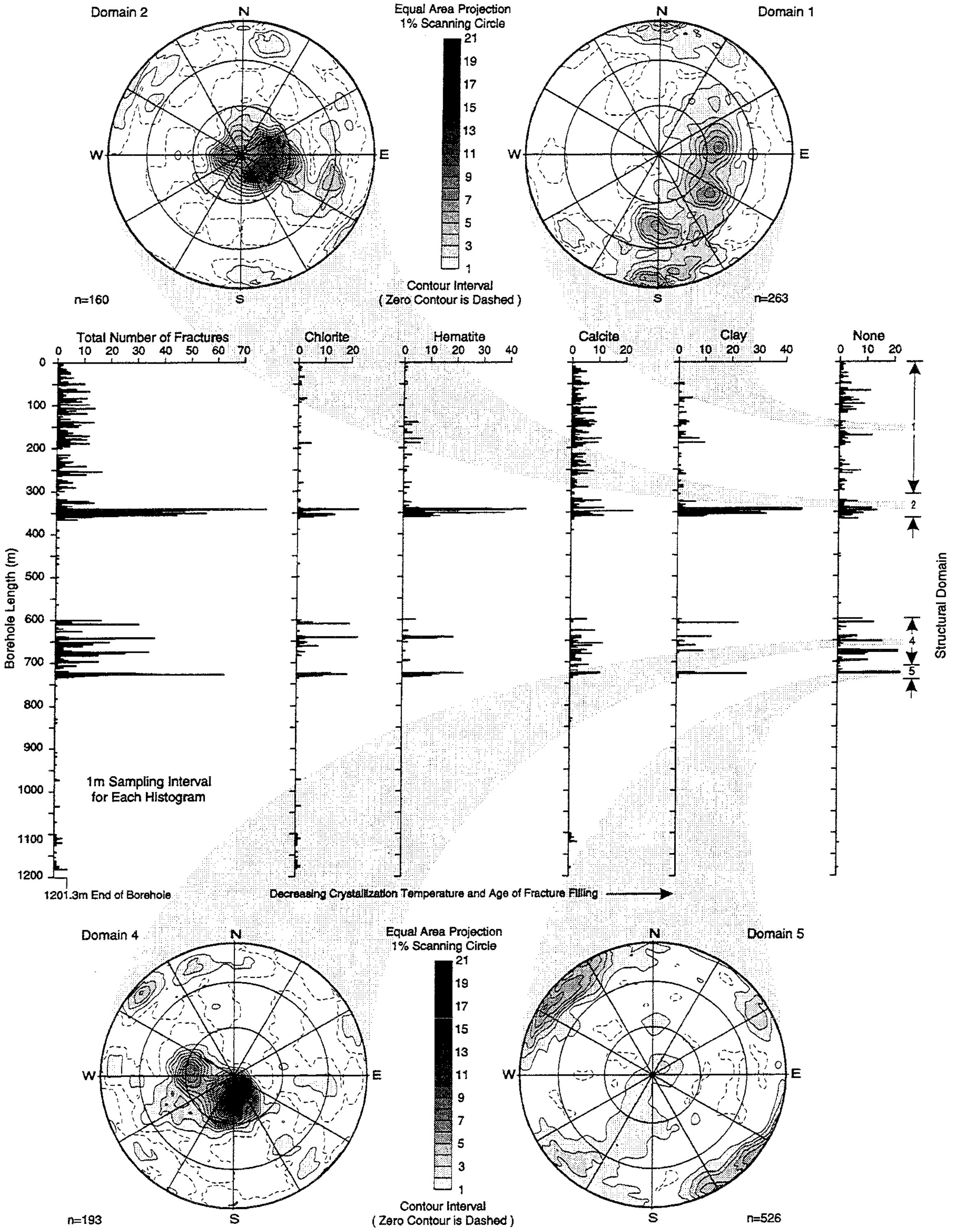


Figure 2-8. Fracture Orientation and Fracture Filling Plots.

Most of the rock property measurements are performed on core samples without open fractures. However, samples from core near to or containing open fractures are used to study fracture infilling minerals and rock alteration.

Hydrogeological and hydrogeochemical measurements are generally made in the boreholes after drilling is completed and when the core log and geophysical logs are available to help in planning where the measurements should be made. However, in some instances it may be desirable or necessary to interrupt the drilling of a borehole to determine the permeability of a borehole interval, to measure the hydraulic head in a borehole interval, or to collect samples of the groundwater encountered. AECL has developed and tested methods for obtaining hydrogeological information during the drilling of boreholes (Davison 1980, Raven 1980) as well as in the boreholes after drilling has been completed (Davison 1981, Lee et al. 1983, Davison 1984a, Raven et al. 1987). These methods are discussed in Section 2.5.2.3.

After the drilling operation is completed, residual drill cuttings and drilling water are removed from the borehole, primarily by pumping water from the borehole. In some cases the upper 100 m of the borehole is drilled at a larger diameter (96 mm or even 125 mm) to allow high capacity submersible pumps to be used for these cleaning operations and subsequent hydraulic testing.

2.5.2.2 Borehole Geophysical Surveys

Shortly after each borehole has been drilled a variety of geophysical surveys are run in the borehole to measure variations in rock properties and to identify fracturing in the rock as well as variations in lithology (Davison et al. 1984, Hillary and Hayles 1985, Soonawala et al. 1990). A wide range of borehole geophysical sensor configurations are used which include single-hole logging and vertical profiling (surface-to-borehole logging).

The suite of 13 geophysical logs (from borehole URL-12 at the Whiteshell Research Area) shown in Figure 2-9 is typical of routine single borehole logging using conventional surveys.

The television and the acoustic televiewer logs provide an optical and near-optical image of the borehole wall. These logs and the fracture log of the borehole core establish the locations of the fractures and fracture zones encountered in the borehole. In Figure 2-9, the acoustic televiewer log indicates intense fracturing at 145 to 155 m, 472 to 482 m, and 668 to 674 m. Less intense fracturing occurs at approximately 260 m and 420 m. All of these intervals are fracture zones. Fractures are also uniformly distributed over the top 160 m section of this borehole. This interval is moderately fractured. The remainder of the intervals are sparsely fractured.

Many of the other geophysical logs also respond to the presence of fractures. The caliper log responds only if there is an increase of greater than about 1 mm in the diameter of the borehole wall over the interval of the fracture zone. Only the fractures in the interval 472 to 482 m cause an anomaly on the caliper log from Borehole URL-12. All the electrical and nuclear logs, except the natural gamma log, respond at the locations of the major fracture zones. The fluid resistivity begins to decrease immediately below the fracture zone at about 260 m, and there is a very large decrease below the fracture zone at 660 m. These decreases in fluid resistivity are caused by increases in the fluid salinity due to saline groundwater entering the borehole from the deeper fracture zones.

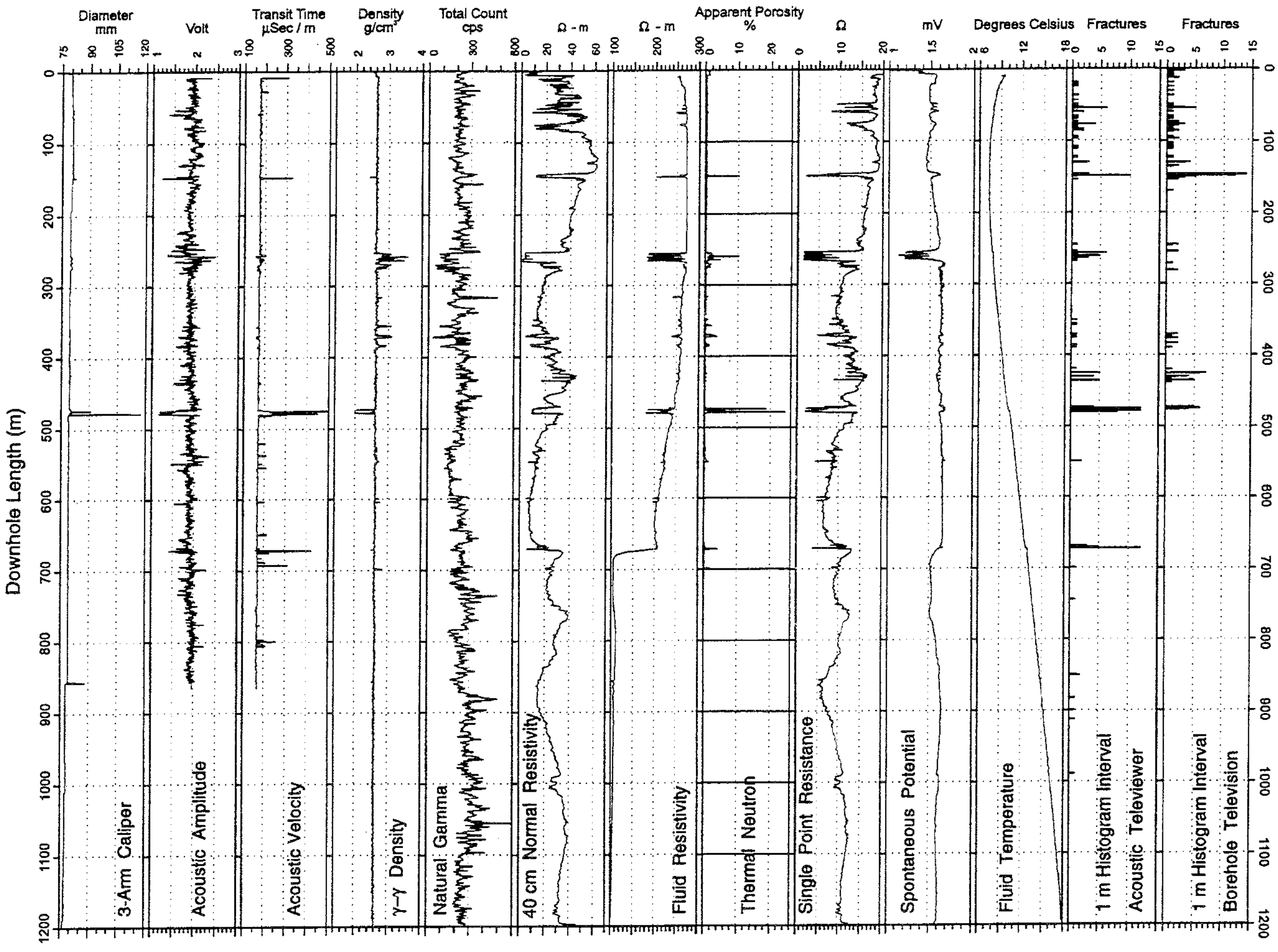


Figure 2-9. Suite of Geophysical Logs for Borehole URL-12.

The fluid temperature increase with depth in Borehole URL-12 is expected because of the natural geothermal gradient in the rock. There is also a temperature inversion in the top 150 m of the borehole, a thermal feature typical of most areas that were covered by continental ice sheets during the last glacial advance over the Canadian Shield (Drury and Lewis 1981, Drury and Taylor 1987).

About 95% of the core from borehole URL-12 has a granitic lithology, so there are few examples of log responses to variations in lithology, although such responses have been observed on the logs from many AECL boreholes (Davison et al. 1984, Soonawala et al. 1990). Responses due to minor occurrences of tonalite and amphibolite, which are rich in mafic minerals, can be seen on the neutron-neutron and density logs from URL-12.

The conventional borehole geophysical logging techniques discussed so far measure the physical properties of rocks within a radius of no more than 15 to 30 cm from the borehole. In order to extend the radius of investigation, particularly for determining the continuity of fractures away from the borehole, AECL uses single hole borehole radar surveys (Figure 2-10).

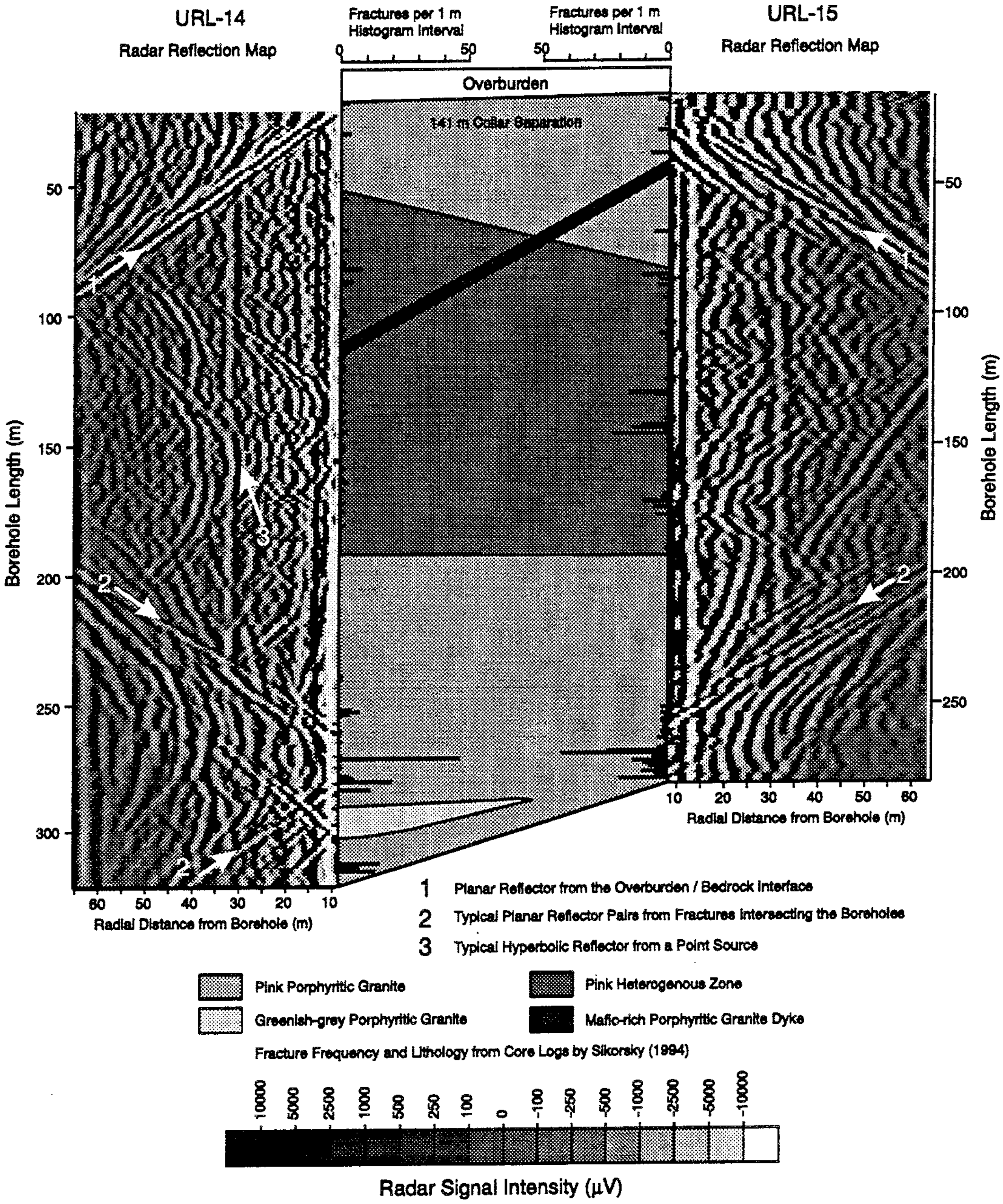


Figure 2-10. Radar Reflections in Boreholes URL-14 and URL-15.

In a single hole radar reflection survey the radar transmitter and receiver antennas are moved along the same hole at a fixed separation distance (AECL generally uses 10 metres) and the propagation time of reflected pulses is measured. When the transmitter and receiver are moved along the hole a characteristic pattern is generated on the radargram depending on the geometry of the reflectors. Point reflectors give rise to hyperbolic reflections while reflections from fracture planes are represented by lines.

AECL's experience in the granitic rocks of the Whiteshell Research Area is that fractures can be traced by the single borehole radar method up to a distance of 80 m from the borehole, depending on the salinity of the porewater in the rock. Boreholes URL-14 and URL-15 are located 130 m apart. The total number of fractures logged in the core of the boreholes are shown in Figure 2-10 along with the lithologic variations. The correlation of the fracture zone at 270 m depth with the reflections in the radargram is evident.

The direction of vertical flow of groundwater in open boreholes can be determined using a high sensitivity heat-pulse flowmeter (Paillet and Hess 1987), or an impeller flowmeter (Figure 2-11). It can also be determined by analyzing changes in thermal anomalies on successive borehole temperature logs made over a period of time (Drury 1984).

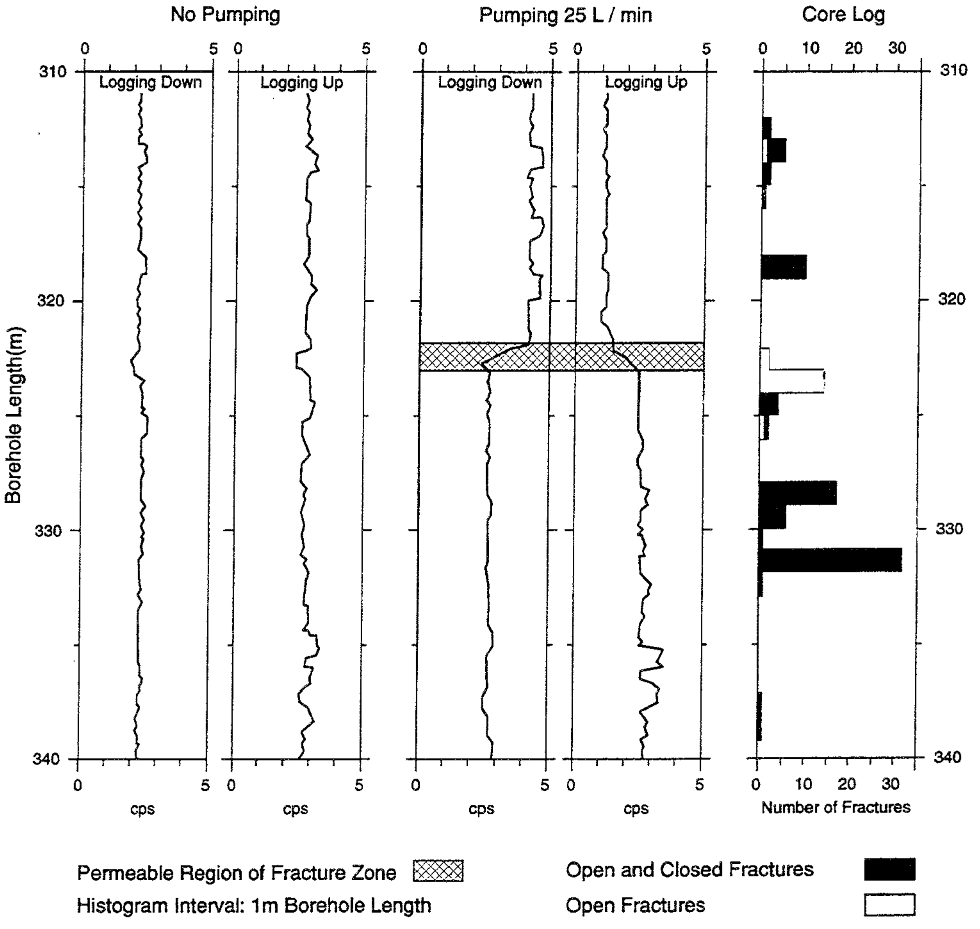


Figure 2-11. Impeller Flowmeter Log in Borehole WN-12.

Impeller flowmeter logs are used to help identify the location of permeable fractures in the boreholes. In impeller flowmeter logging, both the descending and ascending runs are recorded. When water enters a borehole and flows vertically, the blade rotation rate decreases if the logging direction is the same as the flow direction. Conversely, the rotation rate increases if the logging direction is opposite to the flow direction. As is evident in Figure 2-11, the usefulness is greatly enhanced by pumping from the borehole while logging.

2.5.2.3 Hydrogeological Tests

Hydrogeological tests are usually done in the deep boreholes at the grid areas after the boreholes have been completely drilled, the core has been logged and single-hole geophysical surveys have been run. Information from the borehole core log and the geophysical logs is used to select the appropriate borehole intervals for the hydrogeological tests. The test intervals are selected primarily to determine the hydrogeologic properties of the fracture zones and the intervals of moderately fractured rock.

Special equipment consisting of either modified diamond drilling equipment (referred to as a workover rig) or an umbilical cable/winch system is used to raise and lower the hydrogeological test equipment within the boreholes (Figure 2-12).

Hydrogeological tests involve isolating an individual interval of the borehole by means of inflatable rubber packers and injecting or withdrawing water or simply raising or lowering the pressure in the packer-isolated interval. The permeability of the region of the rock surrounding the test interval is calculated by analyzing the variations which occur in the groundwater pressure and groundwater volume during the tests. Other hydrogeological factors such as porosity, spatial variations or boundaries in the permeability conditions surrounding the borehole, and natural groundwater pressure conditions are also inferred from the test data.

Both single borehole and multiple borehole hydraulic testing methods are used in AECL's site investigations. Single borehole testing is used to evaluate the hydrogeologic properties of both fractured and unfractured intervals along the borehole, whereas multiple borehole hydraulic tests are usually used in the fractured intervals to evaluate conditions between boreholes.

In single borehole hydraulic testing, hydraulic pressure changes are monitored only in the borehole being tested, and usually for only a short time (a few hours). As a result, the observed changes in pressure and flow usually result from permeability variations near the borehole (near-field boundary conditions such as skin effects). During multiple borehole hydraulic testing, hydraulic pressure changes are monitored in observation boreholes as well as in the boreholes being tested and the test duration usually ranges from several hours to several days or even a few weeks. The long-duration hydraulic interference tests may show the effects of permeability variations over distances greater than several hundred metres from the borehole being tested (Davison 1984a, Davison and Kozak 1989). Multiple borehole hydraulic tests are discussed in Section 2.5.3.2.

Permeabilities (hydraulic conductivities) as low as about 1×10^{-21} m^2 (1×10^{-14} m/s) and as high as about 1×10^{-10} m^2 (1×10^{-3} m/s) can be determined using AECL's straddle packer equipment and data analysis methods (Raven 1980, Davison 1981, 1982, Lee et al. 1983, Raven et al. 1987).

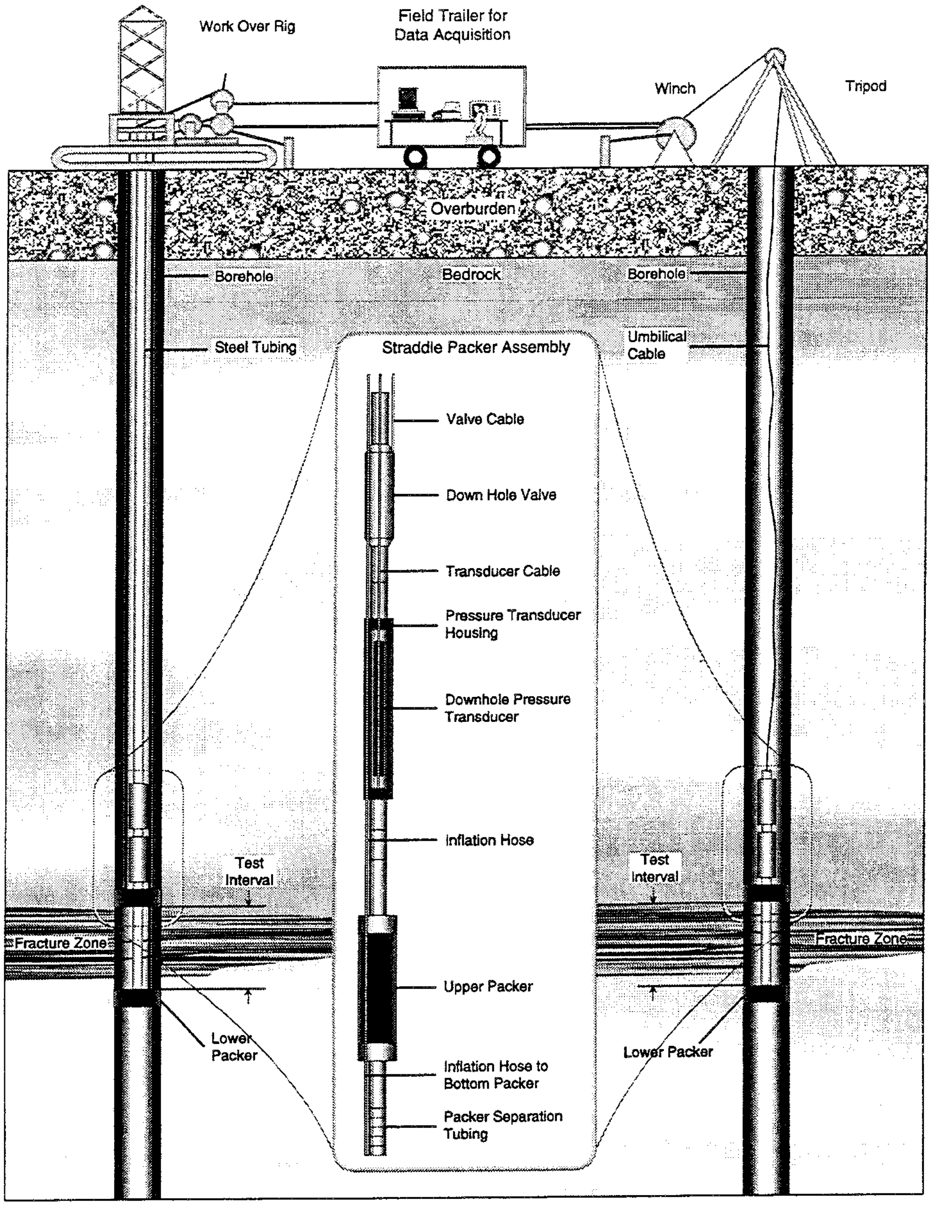


Figure 2-12. Hydrogeological Test Equipment.

Different methods are used for determining the permeability of low permeability and high permeability test intervals. For example, constant pressure/variable flow injection tests or pulse tests are usually used in low permeability test intervals, whereas constant flow/variable pressure injection or withdrawal tests are used in high permeability test intervals (Raven 1980, Davison 1981).

Depending on the test type, hydrogeologic test data are analyzed using a number of flow models, which represent either steady-state or transient pressure conditions. The flow models used by AECL simulate radial-flow, line-source conditions, in a homogeneous, infinite-acting reservoir, under transient or steady-state pressure conditions. The single borehole hydraulic test data are analyzed assuming either transient or steady state conditions (Davison 1980, Raven 1980), whereas the multiple borehole interference test data are analyzed assuming transient conditions (Davison 1981, Davison 1984a).

Single borehole transient pressure test data are analyzed by matching the pressure data with simulated type curves generated by analytical models of infinite acting, partially-closed and closed reservoirs formed by homogeneous, double-porosity and fractured aquifers or conduits (Lee et al. 1983, Kozak and Davison 1992). A computer-assisted type curve fitting method by Gringarten (1986) has also been used to match the transient pressure data. The program INTERP has been used to assist in this analysis.

An example of the permeability data obtained from the single borehole hydraulic testing of one of the deep boreholes at the Whiteshell Research Area is shown in Figure 2-13. The permeability (hydraulic conductivity) surrounding the borehole ranges from about 1.5×10^{-13} m^2 (1×10^{-6} m/s) at a fracture zone located at 70 m depth to about 1.5×10^{-20} m^2 (1×10^{-13} m/s) at an interval of sparsely fractured rock located at about 800 m depth.

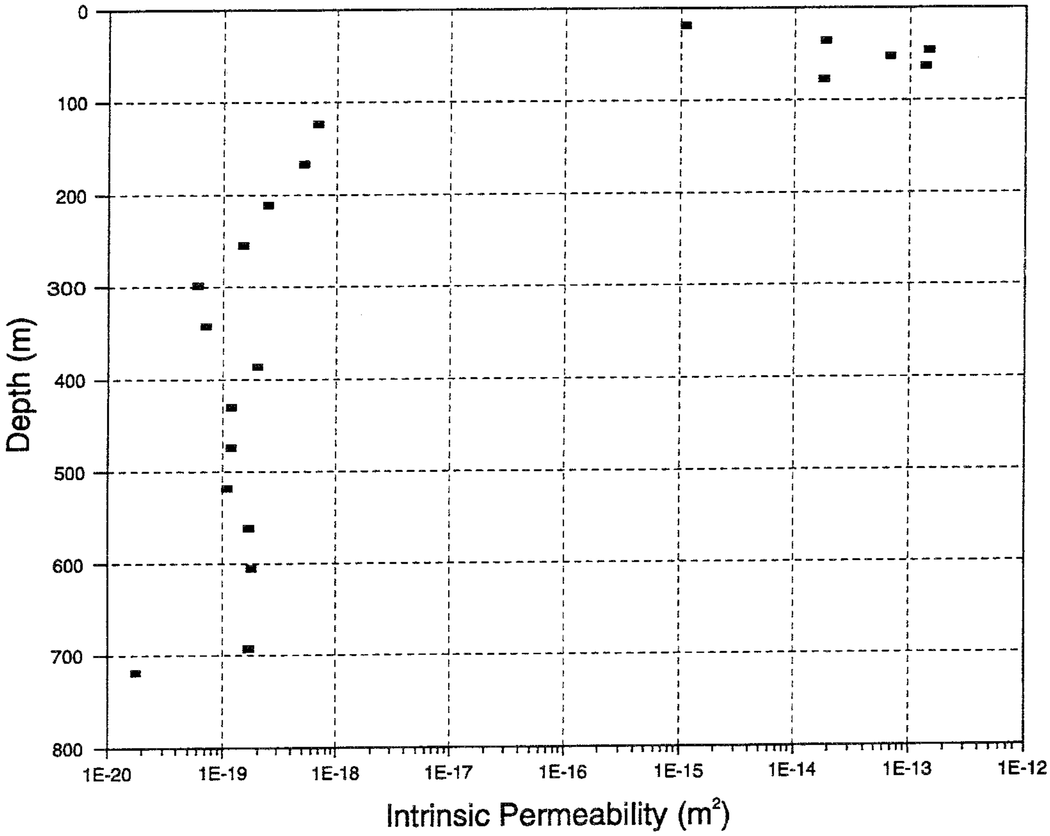


Figure 2-13. Permeability Distribution in Borehole.

2.5.2.4 Hydrogeochemical Sampling

After a borehole has been drilled, groundwater samples are obtained to determine the chemistry of the groundwater at various intervals along the borehole. These samples are obtained by pumping groundwater to surface from between two packers which isolate an interval of the borehole. A typical installation for this work is shown in Figure 2-14.

Special procedures are used to ensure that representative groundwater samples are collected. Different samples are collected and preserved to determine the ion species, dissolved gases, isotopic character, and colloid, micro-organism and organic content of the water (Gascoyne et al. 1987, Ross and Gascoyne 1993a, 1993b). The pH and Eh of the groundwater are measured at the surface using electrochemical probes in a sealed flow-through cell to give reliable estimates of the conditions in situ.

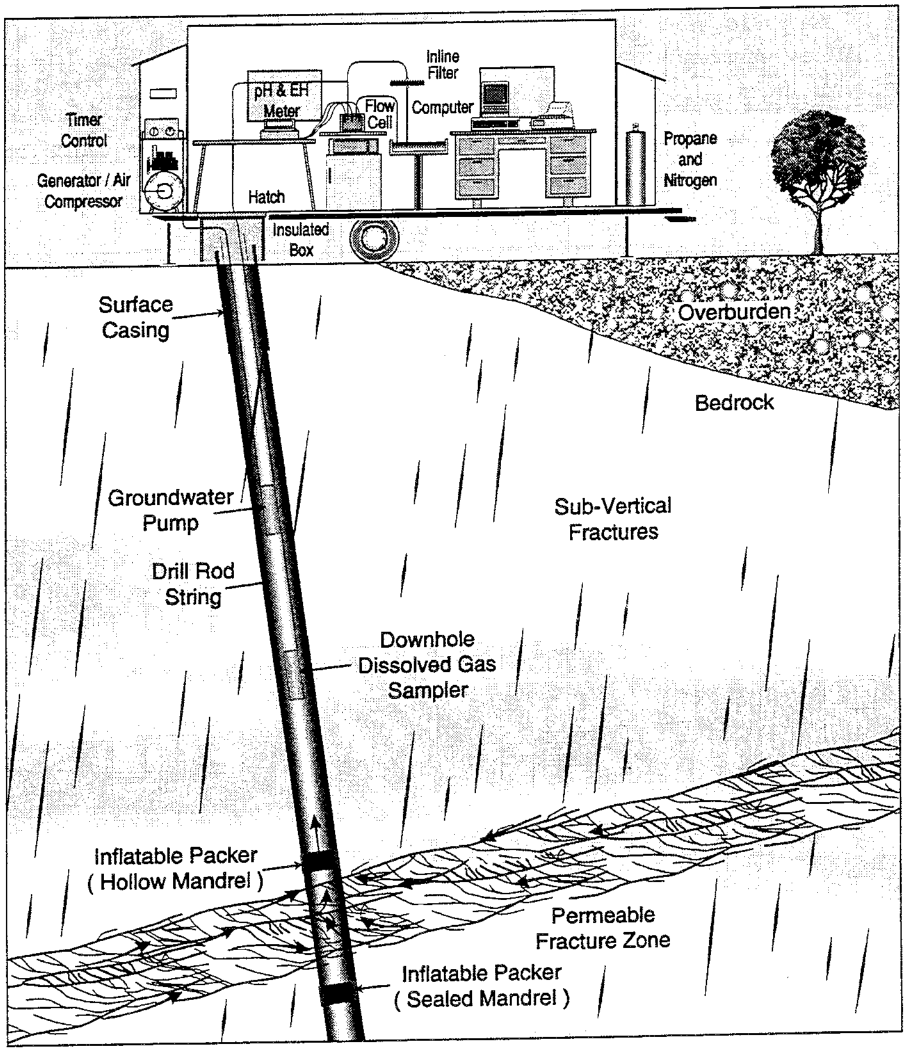


Figure 2-14. Hydrogeochemical Sampling.

Table 2-6 summarizes the parameters determined routinely for groundwater samples collected from borehole intervals to characterize the chemical composition of the groundwater. The pH, Eh and ion concentration data are used to determine the nature of the rock-water interactions that have occurred and to classify the water according to the level of its salinity. The isotope data are used to delineate rock-water interactions and also to determine the relative age and origin of the groundwater and the dissolved solutes (Gascoyne et al. 1987, 1988, Gascoyne and Kamineni 1993).

Shallow recharging groundwaters in most rock types on the Canadian Shield are dilute calcium bicarbonate waters with total dissolved solids (TDS) usually below 0.3 g/L. With longer rock contact, sodium content increases and calcium content decreases due to the dissolution of plagioclase in the rock, precipitation of calcite in fractures, and exchange of calcium for sodium in clay minerals. At the same time, the chloride and sulphate contents of the groundwater begin to increase largely as a result of dissolution of soluble salts (present as fluid inclusions and in pores at grain boundaries) in the rock.

Table 2-6. AECL's Methods for Preservation and Analysis of Groundwater Samples.

Sample	Species/Element	Container	Volume	Filtered	Preservation Methods[1]	Analytical Methods[2]	Maximum Storage Time
ANIONS	HCO_3, SO_4, Cl, Br, F, NO_3, I	PLASTIC	250 mL	YES	REFRIGERATE (4°C)	TITRATION, IC COLORIMETRY	1 MONTH
CATIONS	Na, Ca, Mg, K, Sr, Si, B	PLASTIC	125 mL	YES	4 mL/L HCl	ICPS FLAME AAS	6 MONTHS
TRACE ELEMENTS	Li, Fe, Mn, V, Al + others	PLASTIC	125 mL	YES	8 mL/L $HN0_3$	ICPS COLORIMETRY	6 MONTHS
DISSOLVED ORGANIC CARBON	organic C	GLASS	125 mL	YES	REFRIGERATE (Ag)	INFRARED ANALYZER	28 DAYS
COLLOIDS	Colloidal fractions	PLASTIC	50 L	NO	N_2 PURGE	TANGENTIAL FLOW	7 DAYS
ENVIRONMENTAL ISOTOPES	^2H, ^3H, ^{18}O; ^3H (enriched)	PLASTIC GLASS	125 mL 1 L	YES YES	NONE	MS, LSC ELECTROLYSIS + LSC	>1 YEAR
CARBON ISOTOPES	^{13}C, ^{14}C	PLASTIC	4-100 L	NO	NONE PC,$BaCO_3$ PC, NaOH	MS LSC AMS	1 YEAR
SULPHUR ISOTOPES	$S^{18}O_4$, $^{34}SO_4$	PLASTIC	1-4 L	YES	NONE PC, ion exchange or $BaSO_4$	MS	UNLIMITED
HALOGEN ISOTOPES	^{36}Cl, ^{129}I	PLASTIC	1-4 L	YES	NONE PC, AgCl PC, ion exchange	AMS	UNLIMITED
STRONTIUM ISOTOPES	$^{87}Sr/^{86}Sr$	PLASTIC	250 mL	YES	8 mL/L HNO_3	MS	6 MONTHS
URANIUM AND RADIUM ISOTOPES	U, $^{234}U/^{238}U$, ^{226}Ra	PLASTIC	1-4 L	YES	8 mL/L HNO_3	AS	6 MONTHS
RADON	^{222}Rn	GLASS VIAL	8 mL	NO	NONE	LSC	~3 DAYS
DISSOLVED GASES	H_2, He, 0_2, N_2, CO_2, CH_4, Ar, H_2S	STEEL CYLINDER	50 mL	NO	NONE	MS	28 DAYS
DISSOLVED INERT GASES	He, $^3He/^4He$, Ne isotopes	COPPER TUBE	10 mL	NO	NONE	MS	1 YEAR

1. PC = Preconcentration followed by method used
2. IC = Ion Chromatography,
ICPS = Inductively Coupled Plasma Spectrometry,
AAS = Atomic Absorption Spectrometry,
(A)MS= (Accelerator) Mass Spectrometry,
LSC = Liquid Scintillation Counting,
AS = Alpha Spectrometry

Saline groundwaters that are rich in chloride and sulphate (TDS > 1 g/L) are generally found below 300 m in all the low permeability sparsely fractured rocks at AECL's research areas. More dilute groundwaters are sometimes found deeper than 300 m in highly permeable faults or in intensely fractured zones. Saline groundwaters can also occur at shallower depths in areas where saline groundwaters from depth are discharging to surface. Chloride-enriched, saline groundwaters indicate prolonged rock water contact or mixing with a highly saline groundwater source. Mixing may have occurred if there was intrusion of brine from adjacent or overlying marine sedimentary rocks in the past. Detailed discussions of the hydrogeochemical characteristics and trends in rocks of the Canadian Shield have been given by Frape and Fritz (1987), Gascoyne et al. (1987, 1988, 1989, 1991) and Gascoyne and Kamineni (1993).

2.5.2.5 Determination of In Situ Stress

In situ stress can be determined in exploration boreholes by overcoring. Two approaches have been used. In the approach using the Swedish State Power Board (SSPB) triaxial strain cell (Christiansson 1989), strain gauges are glued on the wall of a pilot hole that is drilled a short distance in advance of the bottom of the borehole at a slightly smaller diameter. In the approach using the AECL Deep Borehole Deformation Gauge (Thompson 1990), an instrument is installed to monitor the diameter of the pilot hole. In both approaches, the larger diameter borehole is then drilled past the cell or gauge to recover it using a special overcore bit.

Both overcore methods were tested at the URL in 1987. At the time, the AECL gauge was preferred because it allowed continual monitoring of the overcoring process, which aids greatly in interpreting the measured deformations. The AECL gauge has been used successfully to borehole depths of about 220 m. Christiansson (1989) reported that an improved SSPB cell also allows continuous monitoring during the overcoring process and has been successfully used to a depth of about 350 m.

The interpretation of deformation associated with overcoring is based on the theory of elasticity with a linear relationship between stress and strain. However, in deep boreholes or at high rock stresses, microcrack development can cause a nonlinear rock response, leading to breaking of the core (core discing), which can prevent successful overcoring. Core discing was encountered at depths of about 300 m below surface in some of the boreholes drilled for overcore measurements at the URL. The occurrence of discing in ordinary core from boreholes would indicate that high stresses are present, as would failure of the borehole wall (borehole breakout), which is sometimes observed in the borehole televiewer data. Analysis of borehole breakouts may provide information about the stress orientation.

In situ stress can also be determined in an exploration borehole by hydraulic fracturing (Haimson and Fairhurst 1969). In hydraulic fracturing, a section of borehole is isolated with a straddle packer system and subjected to progressively greater radial fluid pressure until a fracture in the borehole wall occurs. It is assumed that the pressure in the borehole is sufficient to overcome the tangential stresses acting at the borehole wall plus the rock tensile strength. Once the fracture is created and the pressure system closed or "shut-in", the magnitude of the minimum stress is assumed equivalent to the shut-in pressure (Haimson and Fairhurst 1969).

Inherent in the hydraulic fracture method is the assumption that the hydraulic fracture occurs in the plane parallel to the maximum stress and that the fracture is parallel to the borehole axis. When this does not occur (when the fracture follows a pre-existing zone of weakness in the rock, for example), the interpretation of hydraulic fracturing results is complex and no unique answer exists (Ljunggren and Amadei 1989). Although coaxial fracturing may generally be the case, experience at the URL has been that deeper than 300 m the hydraulic fractures were not coaxial with the borehole but were nearly perpendicular to the borehole axis. This has prevented successful hydraulic fracturing interpretations below 300 m at the URL. AECL is investigating ways to overcome this limitation.

2.5.2.6 Hydrogeological Monitoring Systems

AECL isolates intervals within the boreholes from one another as soon as possible after geophysical logging, hydrogeological testing and geochemical sampling activities are completed. This is done to prevent mixing of groundwater from different permeable intervals and to provide continuing access to zones of interest. The intervals in 76 mm cored boreholes are isolated by installing multiple-interval, multiple-packer (M-P) casing systems; the intervals in percussion-drilled boreholes are isolated by installing multiple-standpipe piezometer systems (Davison 1984a).

M-P casing systems are modular, which allows each borehole to be outfitted with its own specific design to accommodate the particular number, locations and lengths of the intervals of interest. AECL usually designs each module to consist of a pair of inflatable packers with two valves between them, which can be operated to provide access through the casing to the interval. One of the valves is designed to provide access with minimal disturbance to the interval for recording groundwater pressures; the other valve is designed to provide access for groundwater sampling or hydrogeological testing (Figure 2-15A). In the grid area studies at the Whiteshell, East Bull Lake and Atikokan Research Areas, these modular M-P casing systems have been used to isolate from 10 to 30 different intervals in each deep borehole.

Multiple-standpipe piezometer systems (Figure 2-15B) have separate riser standpipes connecting each piezometer interval to ground surface. The multiple standpipes limit the number of intervals that can be monitored, but all intervals can be monitored continuously.

Groundwater pressure is monitored within the M-P casing systems on a regular basis to record how long it takes the pressure to readjust to equilibrium conditions from the disturbances created by drilling, logging and testing the boreholes and also to record the groundwater pressure fluctuations that occur over time at each monitoring interval. Often it can take many months for the groundwater pressures in the monitoring intervals in the low permeability unfractured or sparsely fractured rock to readjust from the disturbances created by the drilling and other testing activities performed in the borehole before the casing system is installed.

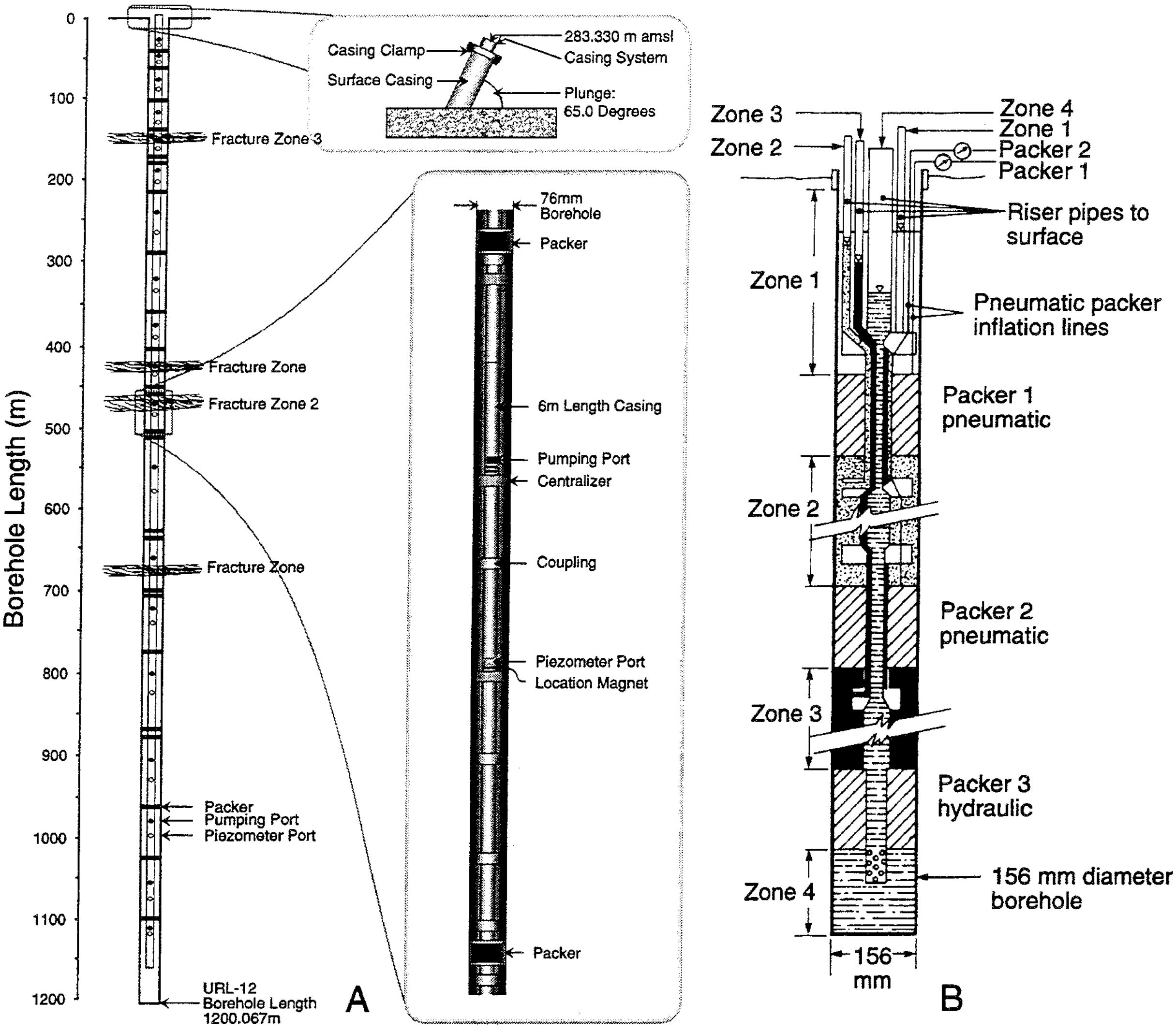


Figure 2-15. Multiple-Interval Casing Systems.

Records of groundwater pressure collected over long periods of time provide useful information about the groundwater pressure distribution in the boreholes as well as information about how these pressures respond to natural factors (earth tide and barometric cycles, rainfall occurrences, climatological cycles) or to human-induced factors (borehole drilling in the vicinity, groundwater pumping tests). Figure 2-16 shows a portion of the groundwater pressure records (converted to water level elevation) from the M-P casing system installed in borehole URL-10.

There is no difficulty in obtaining reliable groundwater pressure measurements from intervals in the M-P casing systems that isolate borehole intervals having permeabilities (hydraulic conductivities) greater than about 1×10^{-18} m^2 (1×10^{-11} m/s). However, it can be very difficult to obtain reliable groundwater pressure readings from intervals in M-P casings if the permeability is lower.

At lower permeability, movement by molecular diffusion is expected to dominate over movement by fluid advection. Not only can it take many months to obtain a stable pressure reading in very low permeability monitoring intervals, but also the pressures which are recorded can be unusually high. Most anomalous groundwater pressures recorded by AECL are believed to reflect actual in situ pressures, which might be caused by some combination of in situ rock stress conditions, presence of high density saline fluids, or slow dynamic response to paleohydrogeologic conditions. However, it is possible that some anomalous pressures are caused by the measurement method itself. AECL is pursuing studies to resolve the causes of the anomalous pressures.

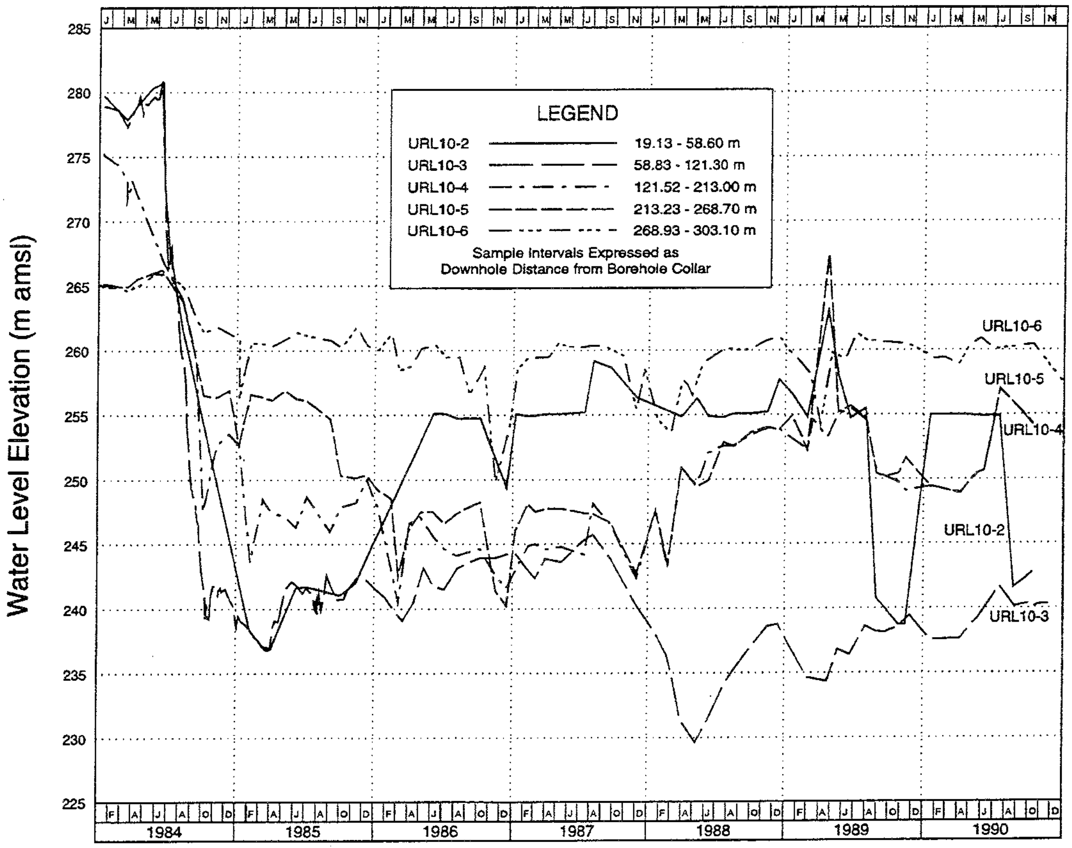


Figure 2-16. Hydrographs from M-P Casing Intervals.

2.5.3 Investigations in Multiple Borehole Arrays at Grid Areas

The investigations conducted in single boreholes identify zones of fracturing and determine whether the zones are permeable in the vicinity of the borehole. However, the information obtained usually represents either a point sample or a line sample of the subsurface conditions. Boundary conditions (such as skin effects, leaky artesian conditions, or low permeability boundaries) in the vicinity of the borehole can be inferred from single borehole hydraulic tests, but not directional information. Moreover, the distance to which conditions can be extrapolated from the borehole is limited.

Multiple borehole investigations (crosshole geophysical surveys and multiple borehole hydraulic tests) are conducted within arrays of boreholes at the grid areas to determine if the permeable fracture zones identified in one borehole are connected to similar zones in other boreholes in a way that would allow groundwater flow between them. Similarly, tests are performed in the boreholes to interpolate the conditions in the rock between one grid area and another.

2.5.3.1 Crosshole Geophysical Surveys

If two boreholes are roughly coplanar and close enough together (within about 400 m), geophysical surveys using the transmission of radar or seismic waves between the boreholes can be made prior to the installation of the multiple-interval casing systems. Crosshole seismic and radar tomographic surveys show good potential for delineating the physical continuity between boreholes of features identified in the individual boreholes (Wong et al. 1983, Olsson et al. 1987, Hayles et al. 1991, Holloway et al. 1992).

Crosshole tomography involves recording a series of seismograms or radargrams with a source located in one borehole and a detector located in another. Detailed coverage of the rock between the boreholes is achieved when many different locations along the two boreholes are used for the positions of the source and the detector.

The transmitted signals from tomographic surveys are analyzed to determine the conditions between the boreholes. Travel time or amplitude of the direct arrival of the transmitted waveform is inverted to create an image of the seismic or radar properties of the region between the boreholes. The inversion is done using computer-assisted tomographic imaging techniques similar in concept to those used in diagnostic medicine, but adapted to the geophysical problem. The Simultaneous Iterative Reconstruction Technique (SIRT) has been modified to reduce the synthetic smearing that can affect travel time inversion. The modified technique is referred to as the Areal Basis Inversion Technique (ABIT). ABIT can resolve targets better than SIRT when multiple targets exist in the tomogram, however, if the positions of the source and detector are not known accurately, artifacts are created with ABIT that degrade the image quality of the tomogram (Serzu et al. 1994).

The frequency range used for crosshole seismic investigations is markedly higher than for traditional exploration seismology (0.5 to 40 kHz rather than 10 to 200 Hz). Consequently, there are important differences between the technology employed in crosshole work and that used in conventional seismology.

In AECL's crosshole seismic survey system, piezoelectric ceramic transducers are used as the active elements in the source and detector because they are controllable, they have a high-frequency response, and they have a good impedance match to plutonic rock conditions. The transducers are packaged in metallic housings to form downhole probes which can operate in water-filled boreholes over 1000 m deep. In the simplest configuration, the detector probes hang freely in the borehole and act as high-frequency hydrophones. Probes with electrically-powered clamping mechanisms to force the seismically active parts firmly against the wall of the borehole are used for better coupling to the rock or for operation in dry boreholes.

The source seismic waveform may be a simple pulse, but a continuous, coded signal using a pseudo-random binary sequence (PRBS) enables transmission over greater distances. AECL uses the PRBS method rather than the more conventional swept-frequency method because it facilitates the use of piezoelectric transducers in the source.

Crosshole radar tomographic surveys can be done between boreholes within about 100 m of each other if the groundwater salinity is not too high. As the groundwater salinity increases the transmission distance for the radar signal decreases.

The results of a crosshole radar tomography survey performed at a frequency of 22 MHz between boreholes WB1 and WB2 are shown in Figure 2-17. Continuity of fracturing between the boreholes in the interval from 150 to 220 m is indicated.

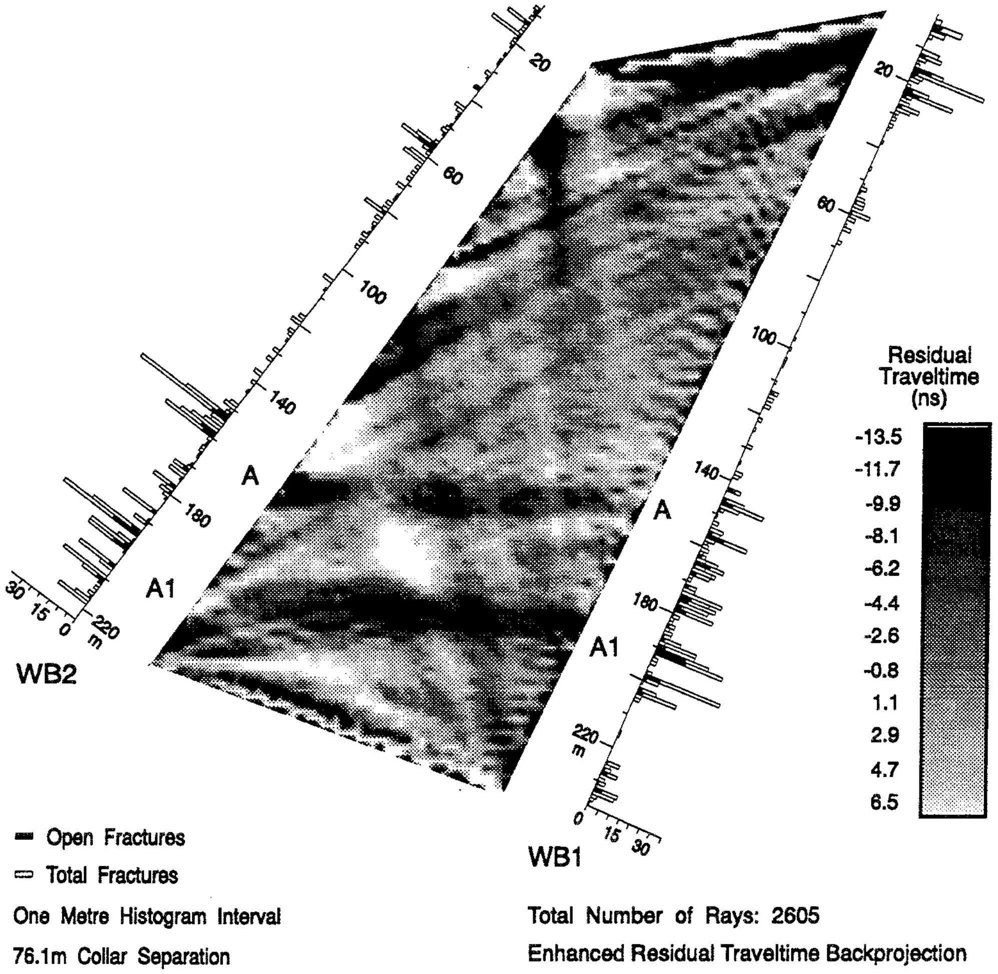


Figure 2-17. Radar Tomogram.

In cases where there are outcrops near to closely-spaced pairs of boreholes at the grid areas, surface radar survey methods and crosshole radar tomography can be combined to provide a very good understanding of the location and continuity of fractures in the rock to a depth of about 80 m. The zones of negative residual travel time on the crosshole tomogram indicate zones of slowed radar wave propagation, which are expected to correspond to locations of intense fracturing. The fracture logs for boreholes WB1 and WB2 show that open fractures are present where zones of negative residual travel time are intersected. The results of surface radar surveys from rock outcrops adjacent to boreholes WB1 and WB2 also show that these fracture zones can be traced away from the boreholes for distances of up to 150 m.

2.5.3.2 Multiple Borehole Hydraulic Interference Tests

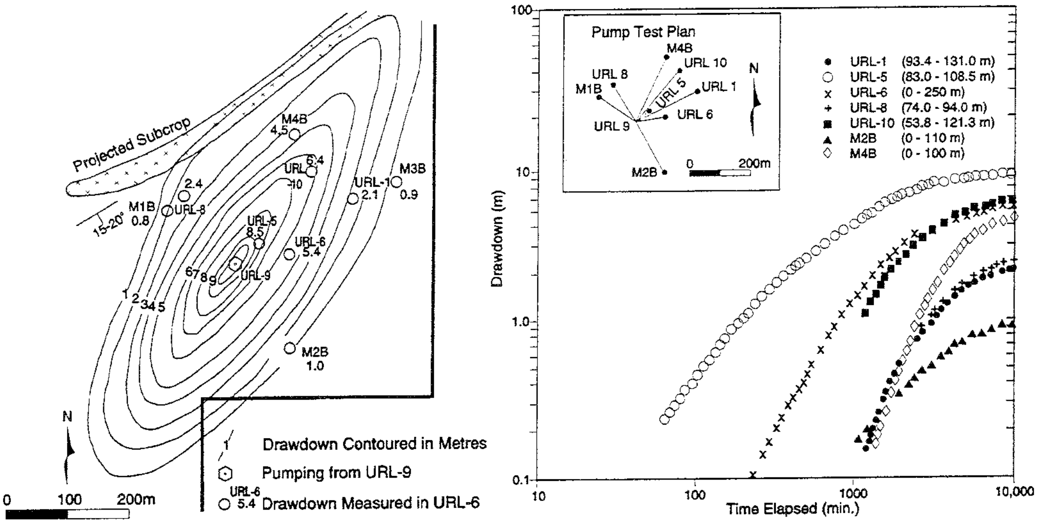
Hydraulic interference tests are performed to assess the hydrogeological characteristics of large volumes of the rock. A hydraulic interference test is done by raising or lowering the groundwater pressure in an interval in one borehole while the groundwater pressure response is monitored in intervals in surrounding boreholes. Hydraulic interference tests are one of the primary methods for developing an understanding of the permeability conditions between boreholes. AECL usually performs interference tests after the multiple-interval casing systems are installed.

After each borehole is fitted with multiple-interval casing systems, groundwater pressure levels in particular fracture zones (isolated by packers) are monitored during the drilling of all subsequent boreholes. Monitoring and interpreting the groundwater pressure responses recorded as new boreholes are drilled provides an early indication of fracture zone interconnectivity and of the areal extent, permeability anisotropy, and hydraulic boundary characteristics of the fracture zones (Davison and Simmons 1983, Davison 1984a).

Subsequently, pulse or pumping tests are done in selected borehole test intervals, while monitoring responses in adjacent boreholes. Data from such tests are used to determine the storage and permeability characteristics of the fracture zones surrounding low permeability rock blocks and to infer the geometry and orientation of the blocks. The results of hydraulic interference tests performed in the major fracture zones at the URL lease area were used to determine both the hydraulic interconnectivity and spatial variability of permeability within large portions of the fracture zones (Davison 1984b, Davison and Kozak 1989, Davison et al. 1990) and to infer the hydrogeologic properties of the sparsely fractured regions of rock between the fracture zones.

The volume of rock that can be affected by a hydraulic interference test depends on a large number of factors, such as the permeability and storage characteristics of the rock and the size and duration of the groundwater pressure disturbance that is created during the test. AECL has obtained information from interference tests at the URL that was useful for characterizing the hydraulic properties of regions of the rock mass located up to 1 km radially away from the pumping or injection borehole.

Figure 2-18 shows the observed responses to a test in FZ-3 at the URL and the interpreted drawdown.

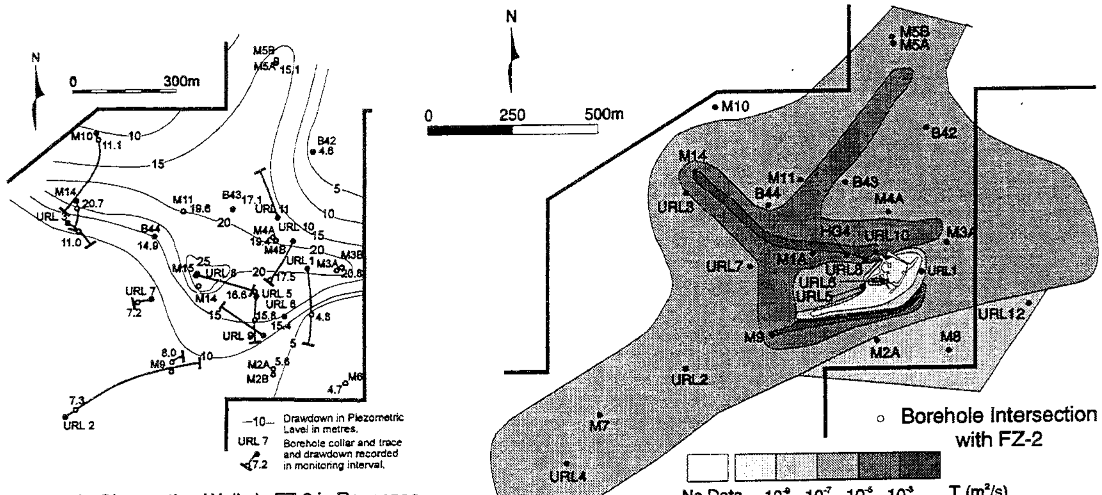


c) Drawdown in Observation Wells in FZ-3 in Response to Pumping at URL-9 (after 6500 min. of Pumping), Sept. 1983 Test

d) Response to Pumping in Observation Well URL-9, Sept. 1983

Figure 2-18. Results from Interference Test in Fracture Zone 3.

Figure 2-19 shows the drawdown from a test in FZ-2 and the interpreted distribution of transmissivity in the zone.



a) Drawdown in Observation Wells in FZ-2 in Response to Pumping at M1A (after 7400 min. of pumping), July 1983 test

b) Transmissivity (T) Pattern within FZ-2

Figure 2-19. Use of Hydraulic Interference Tests.

2.5.3.3 Multiple Borehole Groundwater Tracer Tests

Fracture zone porosity, permeability and dispersion characteristics are determined by performing and analyzing multiple-borehole groundwater tracer tests. AECL used a series of two-well groundwater tracer tests to determine the solute transport characteristics of a 300 m x 50 m portion of a large fracture zone at the URL site (Frost et al. 1992). Analysis of the results of these tests indicated that porous media equivalent transport models can be used to simulate the tracer transport through large fracture zones provided the models properly account for the spatial variability of the porosity and permeability within the fracture zones. The tracer test results also indicate that as the transport distance increases in the fracture zones the effect of heterogeneity decreases, suggesting that there is a size scale on the order of several thousand square metres at which the solute transport properties of these zones can be adequately represented by average porous media equivalent transport properties (Frost et al. 1992).

The volume usually evaluated by multiple-borehole tracer tests is relatively small (boreholes located up to a hundred metres apart) in comparison to the volume of interest for developing a regional groundwater flow and solute transport model. Nevertheless, the information from tracer tests is very important for gaining an understanding of the spatial variability that exists in the solute transport properties of the major fracture zones. AECL plans to increase the volume investigated by performing multiple-borehole groundwater tracer tests over distances of up to 500 m in the major fracture zones at the URL lease area by 1995.

2.5.4 Summary of Borehole Site Investigation Methods

Table 2-7 summarizes the borehole investigation methods that would be used to characterize candidate areas and candidate sites during repository siting. These methods would provide the information needed to identify a candidate site within a candidate area and to select the location for an exploratory shaft at the preferred repository site.

Table 2-7. Investigation Methods Used in Deep Boreholes.

Method	Information
Logging drill core	- geological description of lithologic variations - location, orientation, and geometric characteristics of fractures, veins and faults - nature of fracture openings, infillings and alteration
Fluid temperature	- geothermal gradient - locations of groundwater inflows and outflows
Flowmeter	- locations of more permeable intervals - indication of permeability values
Acoustic televiewer	- location and orientation of fractures (used in re-orienting doubtfully oriented core) - location of other irregularities in the borehole wall such as stress breakouts
Borehole television	- location and orientation of fractures (used in re-orienting doubtfully oriented core) - character of fracture infillings - lithologic variations - estimate of fracture aperture
Standard geophysical logs	- fracture locations - salinity of borehole fluid - lithologic variations
Single hole radar	- location, orientation, and extent of large fractures away from the borehole (up to 70 m)
Cross-hole radar/seismic	- continuity and geometry of features between boreholes
Hydraulic fracturing	- magnitude (and in some cases, orientation) of state of stress in rock
Over-coring	- in situ stress (if core does not disc)
Groundwater sampling	- groundwater chemistry variations
Single borehole testing	- permeability, skin effects, and storage conditions in the immediate vicinity of the borehole - profile of permeability along borehole - hydraulic boundary conditions from long duration tests
Multiple borehole testing (interference tests)	- hydraulic interconnectivity between boreholes - permeability and storage conditions beyond the immediate vicinity of the boreholes - data for use in developing an understanding of the large scale groundwater flow regime and calibrating models
Long-term piezometric pressure monitoring	- data for use in developing an understanding of the large scale groundwater flow regime and evaluating models
Installation of multiple-packer (MP) casing system	- long-term access to hydraulically isolated intervals for hydrogeological testing and monitoring and groundwater sampling

2.6 LOGISTICAL CONSIDERATIONS

2.6.1 Access and Local Infrastructure

Access for the brief field reconnaissance investigations to identify candidate areas within the candidate regions during site screening would be by existing roads, trails, waterways, or air. Because of the limited time available, helicopters and float planes would be the primary means of access where there were no passable roads or trails. No local infrastructure is needed, although local accommodations in existing communities or at hunting and fishing camps would be a great convenience. Except for the longer follow-up investigations in more promising regions, there would probably be no field camps, investigators would move from region to region staying in the most convenient existing accommodations.

Access for the initial reconnaissance investigations at candidate areas during site evaluation could still be by air and water, however operations would be more cost effective if there were road access to a central base camp.

Access for the detailed investigations at grid areas would almost certainly require the construction of roads and upgrading of existing trails for the transport of equipment and personnel. It would also require cutting additional grids of survey lines for geophysical and geological surveys. Although helicopters and float planes would continue to be important for mobility within the area, road access to a central base at the candidate area would be essential for effective field operations.

As soon as detailed investigations began at grid areas, local surveyed bench marks (tied to national geodetic survey benchmarks) would be required for horizontal and vertical control of the coordinates at which information was obtained. Global positioning satellites (GPS) could be used in conjunction with aerial photographs and topographic maps at 1:10 000 or 1:20 000 scale for rapid coordinate control between benchmarks, but borehole elevations would need to be surveyed so that monitoring interval hydrographs could be related to the same datum throughout the candidate area.

A power line and buildings for offices, visitor facilities, core storage and layout, vehicle storage and maintenance, instrument storage and maintenance, and a general machine shop would be needed at the site to carry out effective year-round site investigations, monitoring of site conditions, and visitor and public interaction. Nearby access to a community with living accommodations; restaurants; suppliers for building materials, hardware, and fuel; fire protection; medical services; and at least light manufacturing would be a decided benefit. If there were no community nearby, a camp would need to be maintained with living accommodations, catering, equipment stores, electronic and mechanical maintenance areas, fire protection, security, and provisions for on-site first-aid and rapid evacuation in case of medical emergency.

2.6.2 In-house Versus Contract Staff, Equipment, and Services

AECL favors a hybrid approach to the use of in-house or contract expertise and equipment.

AECL uses in-house expertise and staff for public involvement, planning, decision-making, supervision of contracts and field investigations, training, integration of information, evaluation of the implications of the results of investigations, and quality assurance. These activities require program continuity and an understanding of and commitment to the mission, policies, objectives, responsibilities, and commitments of the organization. Such understanding and commitment cannot be expected of individuals who have divided loyalties or commitments to other clients. In-house expertise is also preferred if services are not readily available on a contract basis (cross-hole seismic and radar surveys, for example), or if services are not needed continuously, but delay in access to the service would be costly or cause loss of important information.

AECL uses in-house or long-term contract (or lease) facilities, equipment, and expertise in situations where they are needed continuously or where availability on a moments notice is required. The choice is made on the basis of cost effectiveness, operational efficiency, or other considerations as illustrated by the following examples.

There are both cost and operational advantages to having in-house equipment and trained staff for standard borehole geophysical surveys and for installing and maintaining borehole monitoring instrumentation. Such equipment is used often, it can be required on very short notice, when needed the need is often urgent, and the cost of mobilizing the equipment to a site is usually high. In addition, staff who must work with monitoring instrumentation on an ongoing basis and live with the quality of the information obtained have great incentives to ensure that the work is well done.

There are both cost and operational disadvantages to having in-house equipment and staff for drilling cored boreholes during the initial surface-based site investigations. There are substantial requirements for drilling at a candidate area and subsequently at a candidate site that allow extensive drilling programs to be planned in advance. Well-qualified contractors are generally available and the large drilling programs encourage very competitive pricing and efficiency of operation that could not be matched using in-house staff and equipment. Because core drilling contractors and their drillers operate in an international marketplace, use of contractors also ensures that up-to-date equipment and very experienced drillers and supervisors can be obtained.

On the other hand, later in the investigations when drilling might be done only periodically, there are advantages to having some in-house core drilling equipment. A significant portion of the cost of short duration drilling contracts is mobilization of drilling equipment. Thus, there may be cost savings in having in-house equipment on site and only contracting for experienced drilling staff.

AECL uses short-term contract services in situations involving performance of specific tasks of short duration or requiring very specialized expertise that is not needed on a continuous basis, so long as the services are readily available. For example, there are well-qualified contractors for both airborne and most ground-based geophysical surveys, which are usually of short duration and do not need to be repeated. Also, universities or other research laboratories are continually developing specialized tests and new methods that are not generally available elsewhere.

2.6.3 Data Management and Quality Assurance

Accurate location of data in both space and time is critical to developing a good understanding of the geotechnical and environmental conditions at a site.

For example, determining the geometry of the domains of interest in the geosphere and of the discrete features within the domains that control their heterogeneity and anisotropy requires that boreholes and the physical features within them are accurately located and oriented in space. Likewise, determining the variations in hydraulic head that control hydraulic gradients in the groundwater flow system requires that the coordinates in space of the points of measurement and the time of measurement be known accurately.

The data from field investigations is most easily manipulated and compared with other data if it is in digital form in a computerized database. Most remotely sensed data and geophysical survey data are obtained in a digital format or are readily transformed by scanning if they are analog images. Information such as maps or line drawings can be scanned or digitized, but the resulting digital files may require considerable editing and verification before they can be used with confidence. Tabular data and data from field or laboratory notebooks can be entered into computer databases manually, but again the resulting files may require considerable editing and verification.

An audit trail for data from site investigations for a repository and any editing or correcting of the data would be essential to meet regulatory requirements for licensing.

In addition, the less manual transcription of data that was done, the less chance there would be for errors to be made. AECL has computerized the core logging, so that core descriptions are entered directly into the computer using an on-screen data entry form. Checking the descriptions and editing for errors is done on the file before it is approved for entry in the master data base by an authorized supervisor. In a licensing process, all these steps could be archived for audit purposes by using date and time stamping and a write-once medium.

With tablet computer technology, collection of certain types of information from outcrops and field notes could be done directly in digital form in the same manner.

For routine activities (core logging, mapping of lithology and fractures in outcrop, water sampling, etc.) standardized procedures would need to be specified in manuals and staff would need to be trained. This would ensure, in so far as possible, that no matter who made an observation (a student on a four month work term or an experienced supervisor) or when it was made (whether in the first reconnaissance or after disposal operations had begun) it would be done consistently. For non-routine activities, the procedure or circumstances would need to be documented and the documentation keyed to the data in the database.

Backup of the data on more than one medium and in more than one location would be essential to its archival preservation.

AECL has implemented a records management system as part of a program to ensure that scientific information from site investigations at field research areas and information about site investigation methods developed during the R&D program is safely stored and will be available if and when site screening and evaluation for a repository begins (Ridgway et al. 1990).

2.6.4 Operational Safety and Good Housekeeping

As with operations at all nuclear facilities, it would be imperative that a strong safety culture be developed and maintained and that good housekeeping be practiced in the field investigations at candidate areas and candidate sites for a repository. This would be in the best interests of the staff because field investigations are hazardous activities and in the best interests of the project because the public perception of the repository would be affected by any accidents (whether nuclear or not) and by the appearance of the site (access roads, ditches, work sites, instrument housings, etc.).

3 DEVELOPING CONCEPTUAL MODELS OF THE GEOSPHERE AND A GEOSPHERE MODEL

3.1 INTRODUCTION

An understanding of the characteristics of the geosphere at a potential disposal site would be essential for selecting a preferred location for a repository, for designing a repository, and for assessing the potential effects of the repository on human health and the natural environment.

Models of the geosphere are representations of the understanding of the geological site characteristics (structure, lithology, stress, temperature, hydraulic head, and rock properties) either visually or mathematically.

The models can be conceptual (a qualitative or schematic representation of the features, characteristics, or distributions of values of properties, such as a map, cross-section, or block diagram) or analytical (a quantitative or mathematical representation, such as a numerical groundwater flow model which implements equations in a computer program).

3.2 STRATEGY FOR THE DEVELOPMENT OF MODELS

AECL's strategy for the development of models for a candidate area or site is illustrated in Figure 3-1, a flow chart showing the steps followed for the preparation of the Geosphere Model used in the postclosure assessment case study done as part of AECL's assessment of the concept of disposal in plutonic rock (Section 1.1). The focus for the selection of information and data from the site investigations would be on properties or characteristics that have the potential to control contaminant movement in the geosphere and, thus, transport of contaminants from the repository to the biosphere.

The information would be interpreted to identify volumes of rock (domains) that differ significantly from one another in their characteristics and to develop conceptual models of the three-dimensional distribution of the domains. As shown in Figure 3-1, the results would be integrated to

- construct a conceptual model of the hydrogeological units (A),
- construct two- and three-dimensional mathematical models for analyzing groundwater flow based on the conceptual model (B),
- identify the pathways for groundwater flow from the repository to areas of groundwater discharge in the biosphere (C), and
- construct a three-dimensional network of one-dimensional transport segments representing pathways for advective and diffusive transport of contaminants from the repository to the biosphere (D).

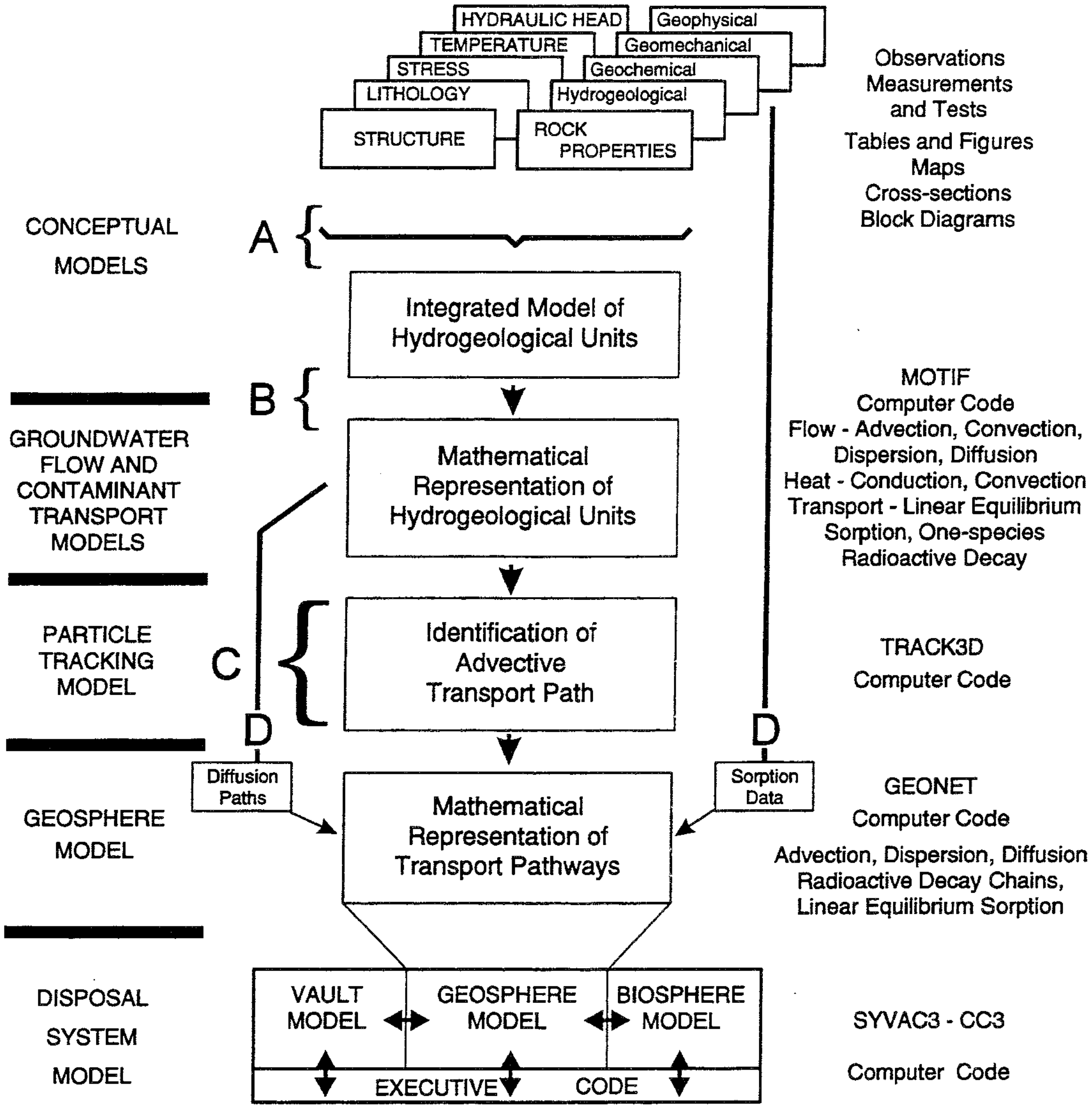


Figure 3-1. Flow Chart for Preparation of a Geosphere Model

3.3 DEVELOPING CONCEPTUAL MODELS OF SITE CHARACTERISTICS

Conceptual models of a site are visual representations of the understanding of site characteristics: geologic structure, lithology, in situ stress, temperature, hydraulic head, and the variability in rock properties (hydrogeological, geochemical, geomechanical, and geophysical).

At a repository site, conceptual models would be used for several important purposes:

- planning the site investigations;
- preparing mathematical models of processes that are expected to be important in the geosphere at the site, either because the processes would occur naturally or because they would occur in response to the construction, operation, and closure of the repository;

- preparing the repository design;
- preparing models that can be used in assessing the performance of the disposal system and in estimating the long-term effects of the repository on human health and the natural environment for comparison with regulatory standards; and
- communicating the understanding of the site to regulatory agencies, representatives of the host community, and members of the public.

3.4 THE CONCEPTUAL HYDROGEOLOGICAL MODEL

Synthesis of the results of all the surveys and borehole investigations would provide the basis for developing an understanding of the groundwater flow systems of the candidate area. On the basis of this understanding, a conceptual model of the groundwater flow conditions would be developed for the candidate area.

The conceptual hydrogeological model would be a representation of the understanding of the distribution of the important hydrogeological characteristics of a potential disposal site and its surroundings. This would be in the form of maps, vertical cross-sections, and three-dimensional block diagrams showing those volumes of the rock that have significantly different hydrogeological properties.

This integrated model of the hydrogeological units would become more detailed as more information became available at the site. At any time, it would reflect the then current understanding of the physical and chemical characteristics of the rock and groundwater that affect groundwater flow and solute transport. The reliability of the conceptual model would be continually evaluated by qualitative comparison of expected conditions to those encountered as information became available from new surveys, boreholes and excavations at the site.

3.5 GOING FROM THE CONCEPTUAL MODEL TO MATHEMATICAL MODELS FOR GROUNDWATER FLOW AND SOLUTE TRANSPORT

A detailed three-dimensional mathematical model would be developed to represent the conceptual hydrogeological model. The mathematical model of the groundwater flow system would be calibrated against the field measurements of hydrogeological and hydrogeochemical conditions and responses to field tests at the various grid area locations. Hydraulic aspects of the model would be tested by predicting in advance the hydraulic responses to multiple borehole hydraulic interference tests and comparing these predictions to the observed responses.

Other aspects of solute transport, such as dispersion, would be incorporated into the model and calibrated against the information obtained from multiple borehole groundwater tracer experiments at the grid areas, albeit usually over shorter distances than the hydraulic tests. Once developed and calibrated using all the available surface and subsurface data from the grid area investigations, this model of the regional solute transport conditions would be used to evaluate and compare alternative locations for a repository and to assist in preparing preliminary safety assessments of disposal systems using various repository designs at alternative locations.

3.6 THE GROUNDWATER FLOW MODEL

The groundwater flow model would be a three-dimensional mathematical representation of the conceptual hydrogeological model for the candidate area or site. The model would be tested by comparisons with problems that have solutions that are known exactly and comparisons with observations from laboratory and field experiments.

The initial model would be calibrated using the existing hydrogeological and chemical data from the site investigations. The model would be used to make quantitative predictions of responses to changes in conditions induced by ongoing activities at the site. The reliability of the model would be continually evaluated by comparing the predicted responses to the observed responses during site evaluation, exploratory excavation, repository construction and operation.

The results of each comparison would be used to recalibrate the model prior to the next set of predictions. For a reliable model, the modifications made during successive recalibrations would be expected to become less significant as more complete information became available at the site.

3.7 THE GEOSPHERE MODEL FOR POSTCLOSURE ASSESSMENT

There would be a variety of possible ways of incorporating the potential pathways for contaminant movement and their important characteristics into a Geosphere Model. AECL has developed a network code called GEONET that was used to represent the important pathways for contaminant movement from the hypothetical repository to the biosphere in the postclosure assessment case study. GEONET is a network of one-dimensional segments connected together in three-dimensional space (Davison et al. 1994b).

In the postclosure assessment case study, the geometry of the network was selected to match the geometrical structure of the conceptual hydrogeologic model, the groundwater velocity distribution predicted using MOTIF, and the transport pathways from the repository to the biosphere. Where modelling indicated advective transport in groundwater was more significant than diffusion, the network geometry was constructed to reflect the averaged flowlines identified using TRACK3D to analyze the groundwater velocity field estimated using MOTIF. Where modelling indicated diffusive transport was more significant than advection, the network geometry was constructed to represent the expected diffusion paths.

3.8 ONGOING EVALUATION AND MODIFICATION OF MODELS

Evaluation of the models would be an integral part of an ongoing iterative process of

- interpreting information to develop a model,
- checking that the model was consistent with the existing information,
- identifying areas where additional investigations could provide new information that would reduce uncertainty in the understanding of the site or could enhance confidence in the model,
- using the model either to predict conditions or characteristics expected in subsequent investigations or to predict responses in the potential fields expected as a consequence of subsequent investigations or activities,
- comparing the conditions actually encountered or the responses actually observed with the predicted conditions or responses, and
- modifying the models as required to reflect the new information.

As iterations continued, the understanding of the site should improve so that uncertainties and significant modifications of the models become more localized at the site. This process should lead to increased confidence in the models and to the identification of volumes of rock within which the properties controlling contaminant transport are known with sufficient confidence for the purposes of repository design, disposal system performance assessment, and site and repository licensing.

4 ILLUSTRATION OF THE APPROACH AT THE URL

4.1 SITE INVESTIGATIONS FOR THE URL

4.1.1 Introduction

The siting and construction of the Underground Research Laboratory (URL) has provided the most extensive and complete example of AECL's approach to site investigations and to the development of geosphere models.

The URL lease area (~5 km^2) is comparable in size to a potential site for a Swedish repository, although it is smaller than the area that would likely be investigated as a candidate site for a Canadian repository (~25 km^2). In addition, the depth of the surface-based site investigations (mostly between 200 m and 500 m, but up to about 1000 m) is in the range being considered for a Swedish repository. Virtually all the geotechnical aspects of surface-based site investigations that would be proposed for use at a potential Canadian repository site have been applied and tested at the URL lease area.

4.1.2 Reconnaissance Investigations

A regional reconnaissance was begun in 1978 to identify a suitable site for the URL on the the Lac du Bonnet Batholith. Seven screening criteria were established for the site: substantial outcrop of plutonic rock, lack of disturbance by previous drilling or excavation, well-established hydrologic boundaries, larger area than 1 km^2, location near the Whiteshell Laboratories, location near an existing road and power line, and availability for long-term lease. Eight potentially suitable locations were identified and the current location was judged to best satisfy the criteria (Simmons and Velie 1985).

The URL lease area was characterized in stages. Reconnaissance investigations were performed in 1980. These included geological mapping of exposed rock outcrops; airborne and ground geophysical surveys; the drilling, sampling, and instrumentation of a series of shallow boreholes into the overburden deposits; and the installation of instrumentation to monitor surface water and meteorological conditions. Evaluation of the reconnaissance geologic data suggested that two lithologic phases of the granite were present, a pink porphyritic phase and a more uniform grey phase. These were regarded as roof and core zones, respectively, of the granitic Lac du Bonnet Batholith (Brown et al. 1984, Stone et al. 1984, Brown et al. 1985). The pink granite contained numerous fractures, most of which had a north-northeast strike and very high dip. The grey granite was massive and virtually free of fractures at surface.

Variations in the resistivity gradient were consistent with the surface distributions of fractured pink granite, unfractured grey granite and xenolithic granite mapped in outcrop.

The depth and distribution of the overburden deposits at the URL lease area were determined by the VLF-EM resistivity technique (Figure 4-1) and were consistent with the results of the overburden drilling. Schlumberger resistivity soundings also produced satisfactory estimates of overburden thickness at particular locations.

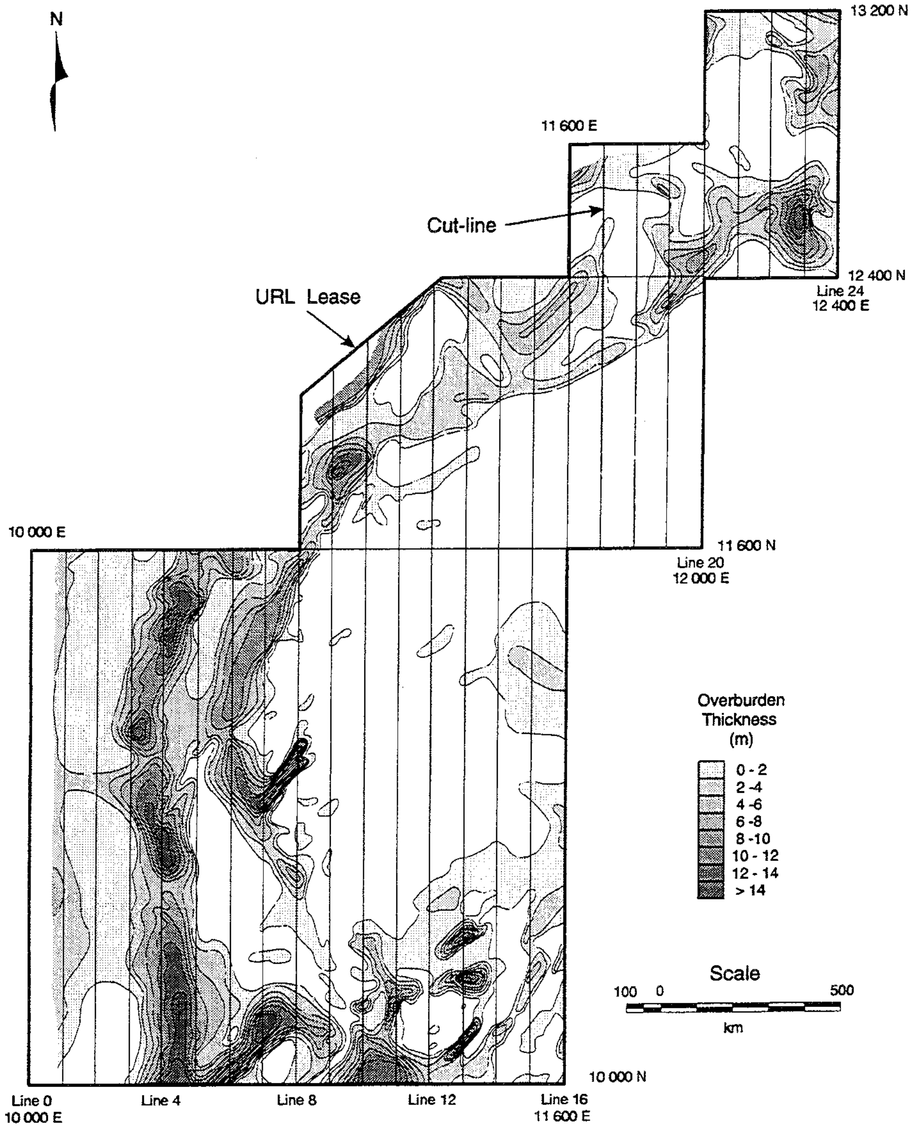


Figure 4-1. Overburden Thickness at the URL from VLF-EM.

Several surface geophysical conductors, were identified by the VLF-EM tilt angle method. It is known from drilling results that one of the conductors corresponds to the intersection of a major low-dip fracture zone with the ground surface. Other conductors may also be similar zones of fracturing in the rock body, although drilling has not been performed to confirm this.

The areal continuity and orientation of one major low-dip fracture zone in the rock mass was indicated by seismic reflection surveys. However, the accuracy of the depth interpretation based on the seismic data is relatively poor when compared with the depth determined subsequently at many locations in boreholes. The initial interpretation of the seismic data also postulated the existence of fracture zones that have not been encountered by the subsequent boreholes.

4.1.3 Detailed Site Investigations

Initially, five deep, cored boreholes were drilled at the URL to check the interpretation of site conditions that had been based on only the surface geological and geophysical data. The borehole information revealed that there were two types of pink granite in the subsurface, one likely related to the early cooling history of the batholith and the other resulting from secondary alteration of the granite minerals by fluids moving through the fractures (Brown et al. 1984). Figure 4-2 shows the interpreted relationships among the phases of the granite and the alteration episodes (Brown et al. 1985).

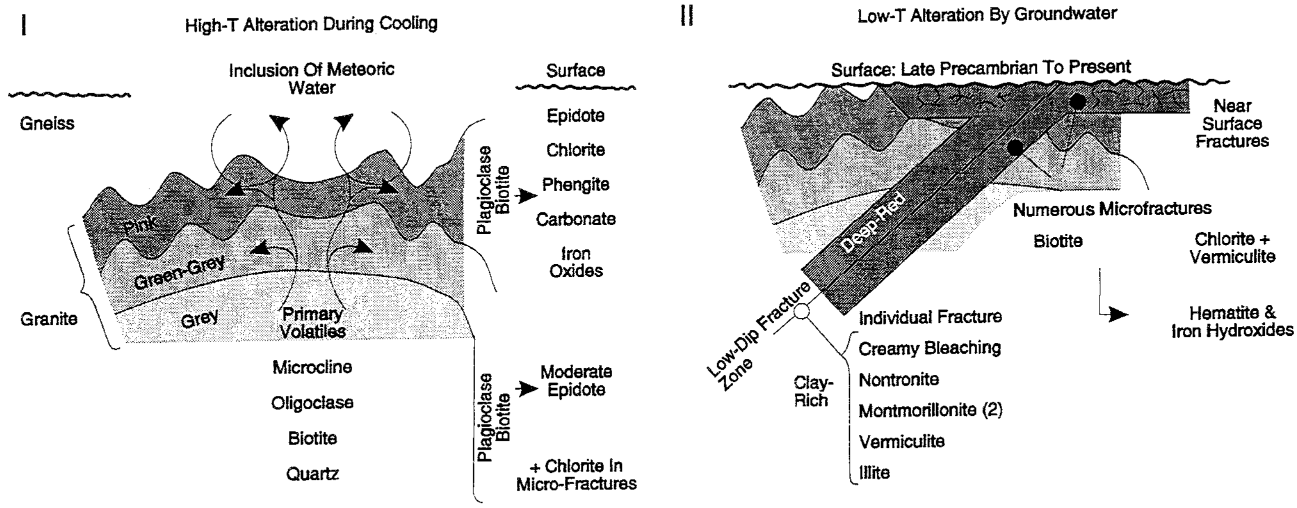


Figure 4-2. Schematic Relationships Among Granitic Phases.

Moderately fractured pink granite occurred primarily in the upper 100 to 200 m of the rock mass with the fracture density highest between 50 and 100 m. The pink alteration occurred along discrete fractures and also in association with extensive low-dip zones of intense fracturing cutting through both the pink and grey granite. The fracture zones exhibited lenticular gouge zones, with reverse dip-slip fault movement. They were partly altered to clay and contained groundwater with relatively high salinity, particularly at depth. The subsurface investigations carried out in the initial five boreholes indicated that there was likely no region where both fractured and sparsely fractured rock would be available for underground experiments at a single level, so a two level underground facility was designed (Brown et al. 1984). The location of a shaft pilot hole was selected to penetrate moderately fractured rock to a depth of about 150 m, sparsely fractured rock between 150 and 260 m, and an intensely fractured zone at about 270 m. At the planned shaft location, sparsely fractured rock occurred below 270 m depth.

The final phase of the surface-based characterization of the URL lease area included drilling eight additional cored boreholes and over thirty air-percussion drill holes to establish a hydrogeological monitoring system in the rock surrounding the planned shaft location (Figure 4-3). The additional borehole control allowed the subsurface geologic structure and the extent and nature of the major low-dip fracture zones to be determined over a large portion of the lease area (Davison 1984b).

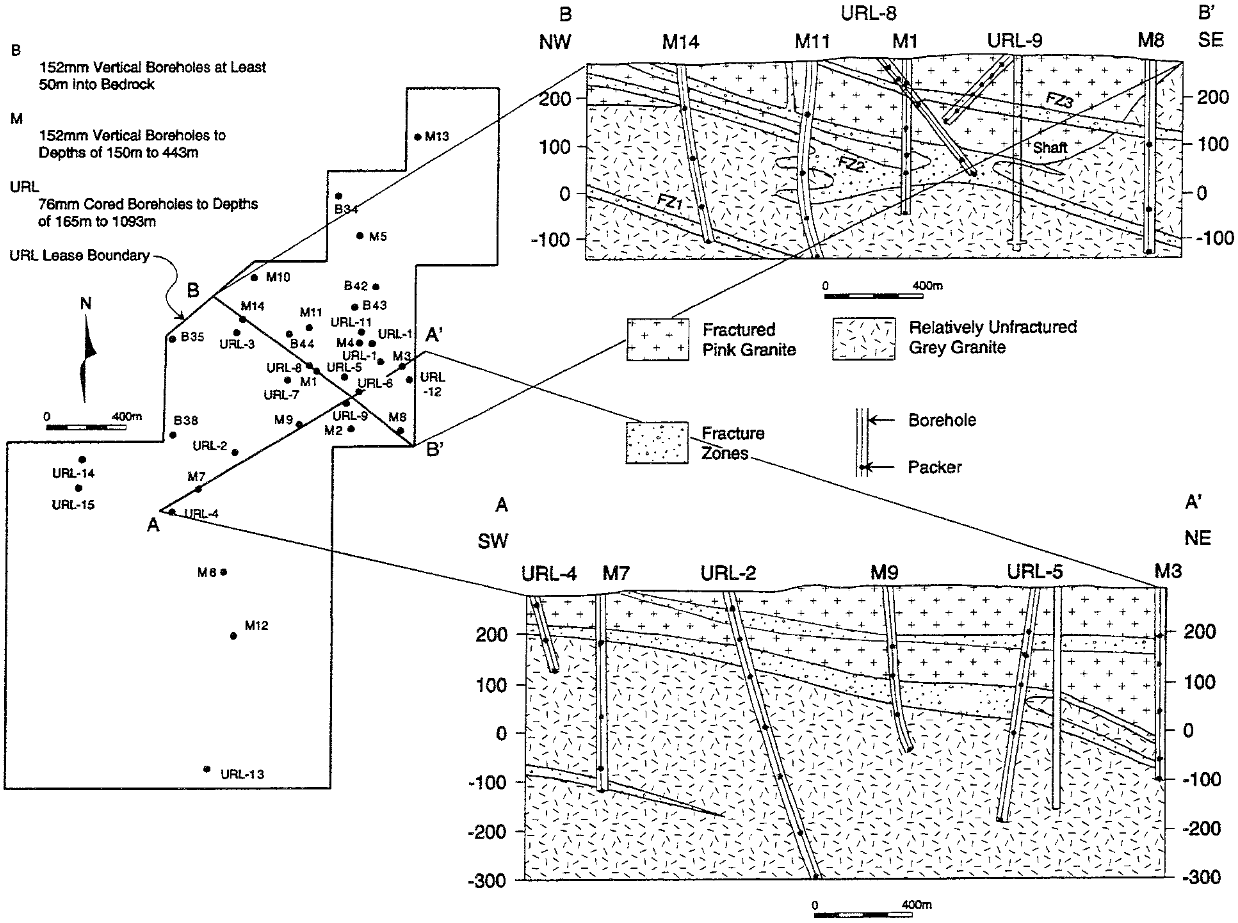


Figure 4-3. Monitoring Intervals Isolated in Boreholes at the URL.

Before any construction of the shafts or tunnels of the URL facility began, the data from the surface-based site investigations were used for a major experiment to evaluate groundwater flow models (the URL Drawdown Experiment). The objective of the experiment was to see if the groundwater pressure responses in the rock mass produced by shaft excavation could be successfully predicted using the finite-element computer code MOTIF (Model Of Transport In Fractured/Porous Media, Guvanasen 1984) for modelling groundwater flow in three dimensions.

A regional groundwater flow model of an area of about 1600 km^2 surrounding the URL lease was calibrated by adjusting groundwater infiltration rates until surface hydraulic heads corresponded to the water table topography. Then, sensitivity analysis with this model was used to establish the hydrogeologic boundary conditions for a more detailed local model of about 20 km^2 describing the groundwater flow conditions in the vicinity of the URL lease area and surrounding the location chosen for the URL shaft (Guvanasen 1984).

Within the local model, the hydrogeological properties of the rock mass and fracture zones were initially estimated from the single borehole hydraulic test data. The model was then calibrated by adjusting the values of the hydraulic parameters within the fractured and non-fractured zones of the model until there was good agreement both between the calculated and measured steady state piezometric values and the calculated transient piezometric responses and field measurements made during the multiple borehole interference tests (such as those shown in Figures 2-19 and 2-20). Following this calibration, the hydrogeologic model was used to predict at 171 locations the groundwater pressure responses to the construction of the shaft to a depth of 255 m (Guvanasen et al. 1985). These 171 locations corresponded to the locations of packer-isolated groundwater pressure monitoring intervals where measurements of the drawdown could be made (Figure 4-3). A period of approximately two years was simulated, and the rate of groundwater inflow to the shaft excavation was also predicted.

Groundwater pressure levels and groundwater seepage rates have been recorded at the URL site since shaft sinking began in 1984 May. These records allow a comprehensive comparison of actual responses to shaft construction with the predicted responses. Generally, the model predicted very well the spatial and temporal pattern of the groundwater pressure responses within the variably fractured rock mass and within the major fracture zones. It also predicted well the trend of flow rate with time, but overestimated the groundwater inflow rates to the shaft by a factor of about 3. Figure 4-4 shows comparisons of the predicted groundwater pressure responses with the observed responses for two of the 171 intervals (Davison 1986).

On the basis of the results of the modelling and the monitoring of the hydrogeologic disturbance caused by initial shaft sinking, AECL has concluded that field data can be incorporated into models to adequately represent groundwater flow in fractured plutonic rock when designing a repository and assessing its performance. The results support the conceptual groundwater flow model that was developed for the URL site before any underground shaft construction began. The results also support the numerical approach and calibration procedure used to describe mathematically the hydraulic aspects of the groundwater flow system at the URL site.

The URL Drawdown Experiment demonstrated that the porous media equivalent approach could be used successfully to describe the hydraulic properties of the fractured rock mass, so long as the location, geometry and spatial variability of the hydraulic properties of the fracture zones were treated discretely in the models. This experiment was an important demonstration of many of the detailed site evaluation methods that would be used to characterize and model groundwater flow and solute transport conditions at a repository site in plutonic rock.

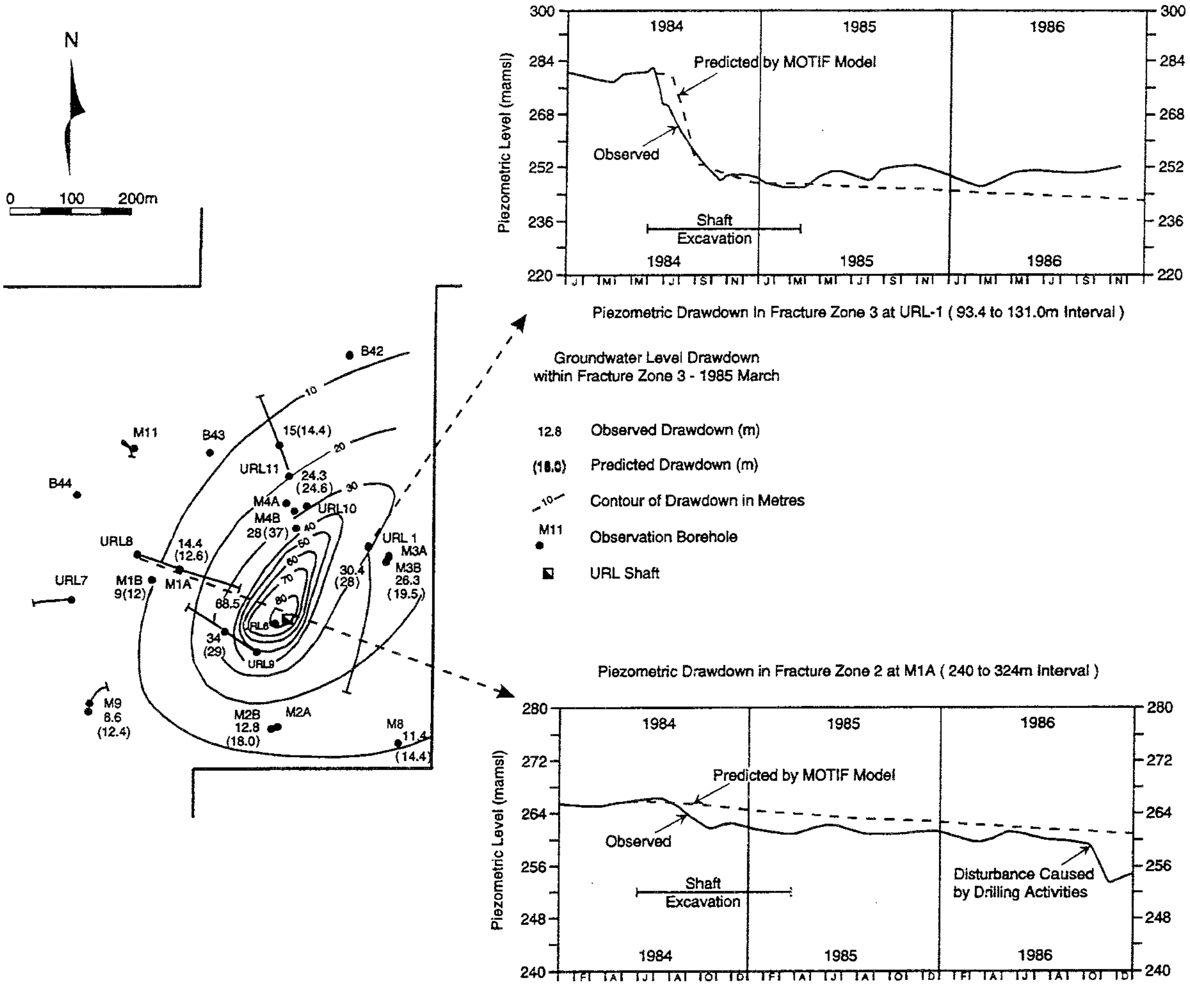


Figure 4-4. Comparison of Predicted and Observed Responses in Two Monitoring Intervals at the URL.

The monitoring of the hydrogeological response and hydrogeochemical changes around the URL excavations will continue until the underground facilities are closed. As the experimental program at the URL continues, the monitoring is expected to provide additional insight into groundwater flow and water-rock interactions in fractured plutonic rock. For example, the inflow of groundwater to the URL has begun to decrease at the same time that groundwater pressures in monitored intervals have increased. This suggests that there may be changes in permeability taking place along the pathways followed by groundwater that enters the URL excavations. Work is underway to investigate this phenomenon.

4.2 DEVELOPMENT OF CONCEPTUAL MODELS FOR THE URL SITE

4.2.1 Introduction

The initial conceptual models for the URL site primarily summarized the understanding of the geometry of the various domains (litho-structural, fracture, geomechanical, geochemical, hydrogeological) developed on the basis of the information from the surface-based site investigations. The understanding from the conceptual models of the separate domains was then integrated into a conceptual model of the hydrogeological units at the site that could be used as a basis for developing mathematical models of groundwater flow and solute transport.

4.2.2 Identification of Litho-structural and Fracture Domains

Litho-structural domains in the Lac du Bonnet Batholith are distinguished on the basis of the dominant lithology, the gross fabric, the relative abundance of late magmatic segregations, and the orientation of the dominant fabric elements (Everitt and Brown, 1986). The domains are recognized based on layering of three main types of granite: a massive to moderately gneissic homogeneous granite; a gneissic heterogeneous granite with xenolithic, leucocratic, and pegmatitic layers; and a xenolithic granite (Figure 4-5A)

On the basis of the schlieric banding, it was established that the URL lease area is located on the eastern flank of an antiform fold structure in the batholith. At the URL, the domains define large-scale layers with northeast strike and southeast dip. The three low-dip fracture zones and associated splays are aligned parallel to this layering. Fracture Zone 2 (FZ2) and FZ3 are generally confined to the xenolithic zones or their margins.

The fracture zones divide the rock mass into blocks. Fracture domains are defined within these blocks depending on the pattern and frequency of the fractures (Figure 4-5B) In Fracture Domains A, B and C, there are one or more sets of subvertical fractures. In Fracture Domain D, fractures are rare or absent.

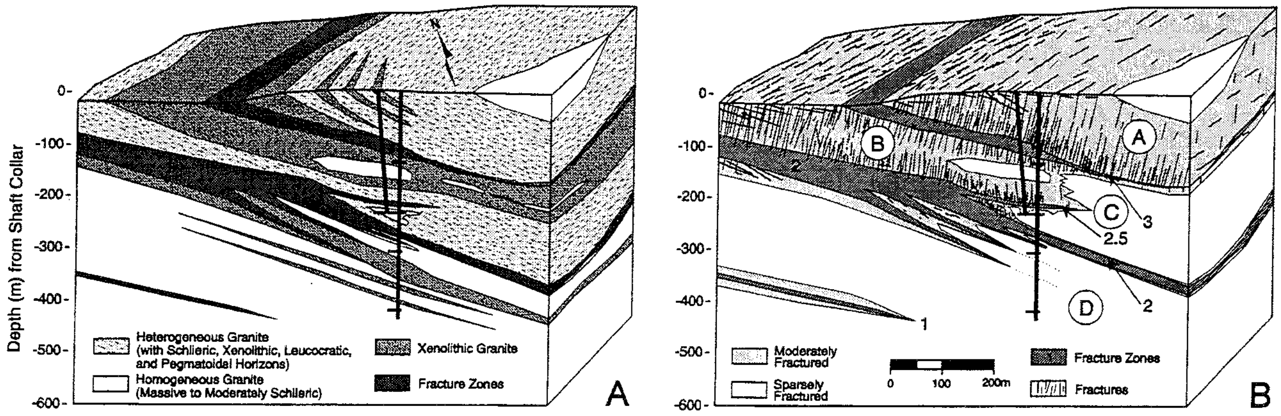


Figure 4-5. Litho-structural and Fracture Domains at the URL.

4.2.3 Identification of Geomechanical Domains

It is unlikely that geomechanical domains would be identified before an exploratory shaft was excavated at a repository site, although indications of stress conditions may be obtained from overcore or hydrofracture tests in exploration boreholes.

The large-scale geomechanical domains at the URL were first identified from stress data collected in the shaft. The domains are distinguished on the basis of changes in the maximum horizontal stress orientation with depth. Above FZ2 the maximum horizontal stress is oriented parallel to the major subvertical fracture set and strikes about 040°; below FZ2 the maximum horizontal stress is aligned with the dip direction of the fracture zone and strikes about 130°.

4.2.4 Identification of Geochemical Domains

Geochemical domains are distinguished on the basis of the distribution of groundwater chemistry in the rock mass and the distribution of minerals in fracture zones and as fracture fillings in moderately fractured rock.

Groundwater sampling and analysis during the hydrogeological testing program indicated that each of the three low-dip fracture zones contained a chemically distinct groundwater (Figure 4-6). The shallowest fracture zone contained a dilute Ca-HCO_3 groundwater that evolved towards a more alkaline, Na-HCO_3 composition along the direction of flow and with greater depth. The middle fracture zone contained a more brackish, Na-Ca-HCO_3-Cl type groundwater. To the northwest of the URL, the deepest fracture zone contained a saline Ca-Na-Cl-SO_4 type groundwater with a total dissolved solids content as high as 15 g/L.

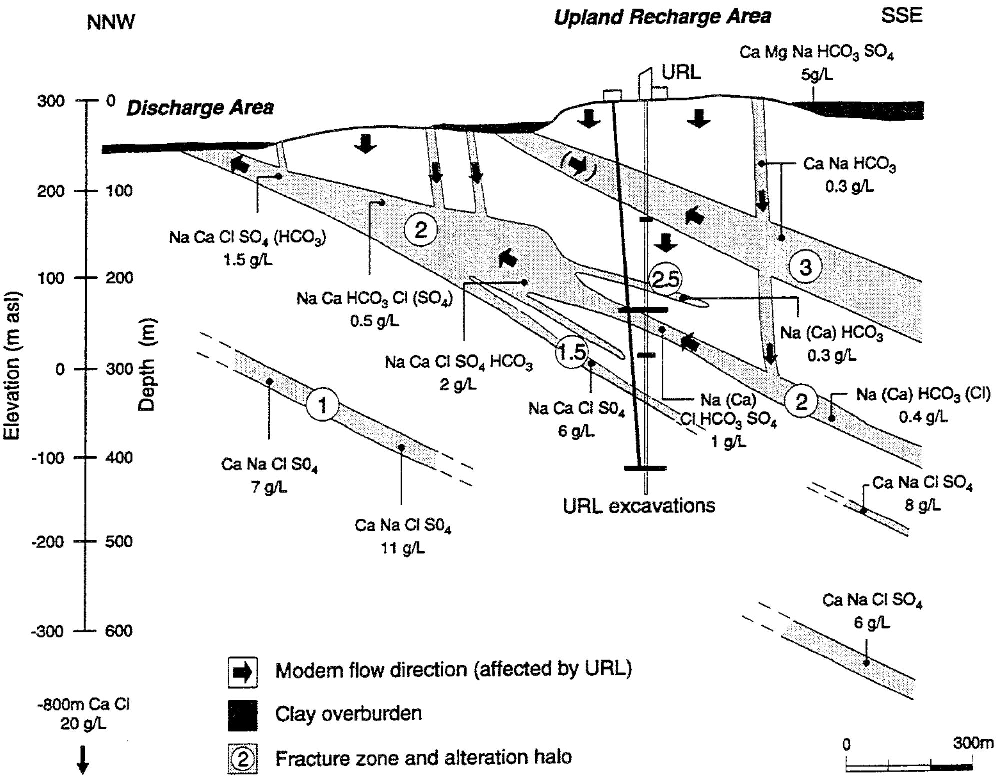


Figure 4-6. Variations in Groundwater Composition in the Rock at the URL.

Illite, chlorite, muscovite, calcite, and iron oxides occur in both fracture zones and as fracture fillings in moderately fractured rock; however, calcite dominates in the subvertical fractures in moderately fractured rock, particularly at shallow depth (Gascoyne and Kamineni 1992).

4.2.5 Identification of Hydrogeological Domains

Extensive hydrogeological testing was done in the boreholes and hydrologic responses in packer-isolated intervals in existing boreholes were monitored as new holes were drilled. This hydrogeological information was used in conjunction with borehole geological and geophysical logs and groundwater sampling to develop a conceptual model of the hydrogeological conditions on the URL lease area.

The large-scale hydrogeological domains at the URL are distinguished on the basis of the spacing of open or potentially water bearing fractures in the rock. Three domains are recognized:

- fracture zones, which are volumes of intensely fractured rock;
- moderately fractured rock, which are volumes of rock containing a small number of sets of relatively widely spaced discrete fractures; and
- sparsely fractured rock, which are volumes of rock containing microcracks and very sparsely distributed discrete fractures that, as a rule, are not interconnected.

The fracture zones are usually only a few metres thick, except at intersections with splays where they may thicken to a few tens of metres. There is commonly a thinner cataclastic zone within the fracture zone. The three extensive, low-dip fracture zones at the URL have sufficiently high porosity and permeability compared with the rest of the rock mass to control the pattern of groundwater flow at the site (Figure 4-7, Davison 1984b). However, significant spatial variability in permeability can occur (Davison and Kozak 1989); the permeability in FZ2 ranges over six orders of magnitude with channel-like distributions of both high and low permeability (Figure 2-20). Thus, the fracture zones at the URL are the principal pathways for groundwater flow and solute transport.

The moderately fractured rock is commonly present adjacent to the fracture zones, between FZ2 and FZ3 to a depth of about 250 m, and between FZ3 and the surface, except in a local area where sparsely fractured rock occurs at surface and to a depth of up to about 50 m. At the URL there may be from one to three subvertical fracture sets present (Figure 4-5) plus random fractures and low-dip sheeting fractures very near surface. Groundwater flow and solute transport through the moderately fractured rock takes place primarily along the discrete fractures. The remainder of the rock volume has low permeability and porosity. The fracture set with a northeast strike is better developed than the other sets (closer fracture spacing and greater fracture lengths in outcrop). This better development is believed to be the cause of the horizontal anisotropy in permeability observed in responses to pump tests both in the moderately fractured rock and in FZ3 (Figure 2-19).

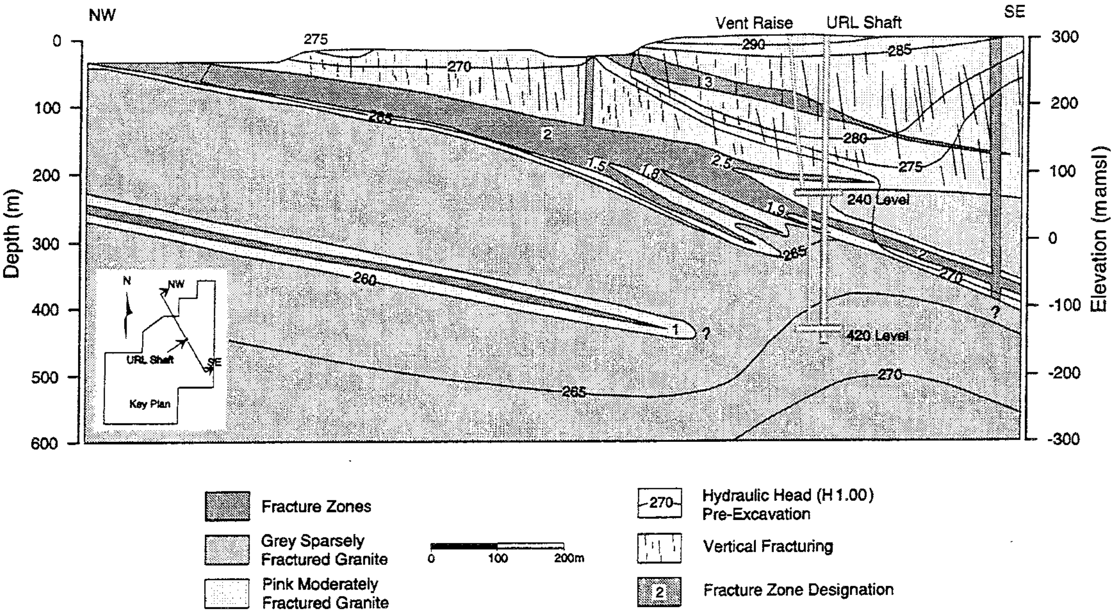


Figure 4-7. Groundwater Flow Pattern in the Rock at the URL.

Sparsely fractured rock occurs below a depth of about 200 m except in the immediate vicinity of the fracture zones. There are few discrete fractures in the sparsely fractured rock at the URL and those few that have been encountered have not been hydraulically active. The permeability and porosity results from poorly interconnected microcracks and grain boundary pores and is very low. Significant groundwater flow probably does not take place and transport would be expected to be by diffusion.

4.2.6 Going from the Conceptual Models of Domains to the Geosphere Model Used in a Postclosure Assessment Case Study of the Potential Effects of a Hypothetical Repository at the URL

AECL has used the surface-based site investigation information from the URL as the basis for developing a Geosphere Model that was used in a postclosure performance assessment case study of a hypothetical repository at a depth of 500 m (Davison et al. 1994b, Goodwin et al. 1994).

Most of the information about the rock, such as the orientation and properties of fracture zones, was obtained from the surface-based site investigations at the URL undertaken before excavation of the shaft in 1984. For features off the URL site where detailed borehole information was not available, assumptions about characteristics at depth were made on the basis of information obtained from geological mapping and geophysical surveys from surface.

Figures 4-8 and 4-9 show the position of the hypothetical repository and the relationship between components of the three-dimensional mathematical model for groundwater flow developed for the case study and the conceptual model of hydrogeological units at the URL. The MOTIF finite element computer code was used to estimate the groundwater flow field (the geometry of the flow paths, the hydraulic heads, and the locations of groundwater recharge and discharge).

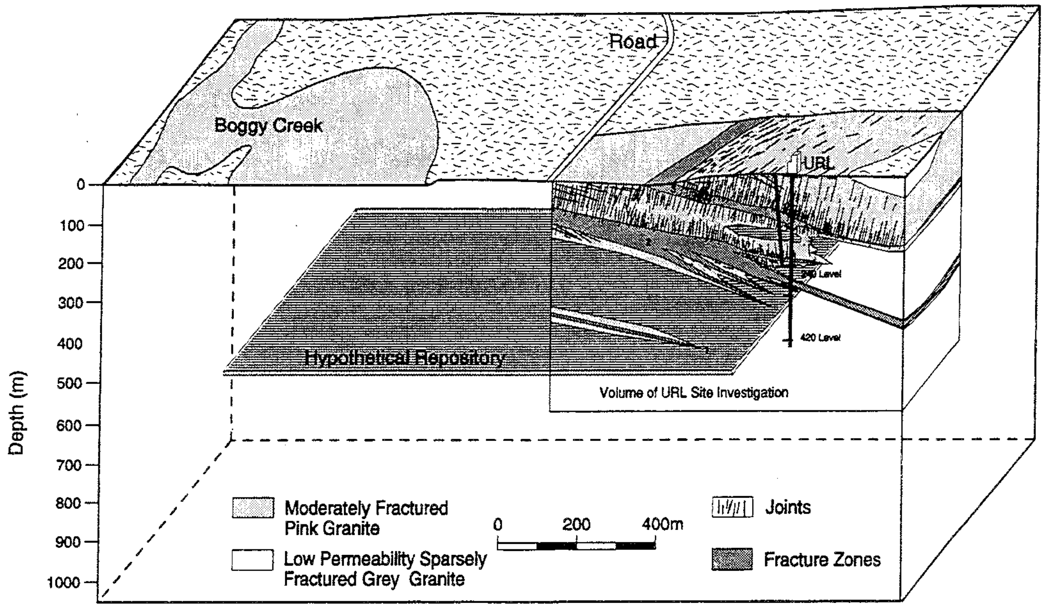


Figure 4-8. Conceptual Model of Hydrogeological Units at the URL.

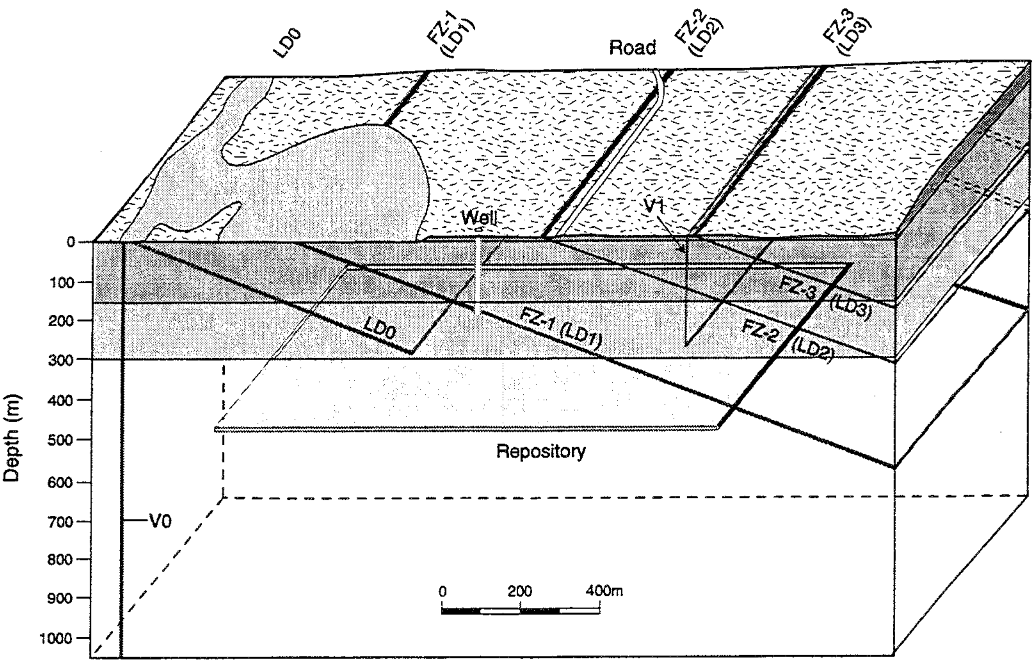


Figure 4-9. Components in the Three-dimensional Mathematical Model for Groundwater Flow.

Particle tracking showed that contaminants from the hypothetical repository would enter pathways for groundwater flow and discharge to nearby surface water bodies. The geometry of the pathways was controlled by the local configuration of the topography and the local geometry of the fracture zones (Figure 4-10).

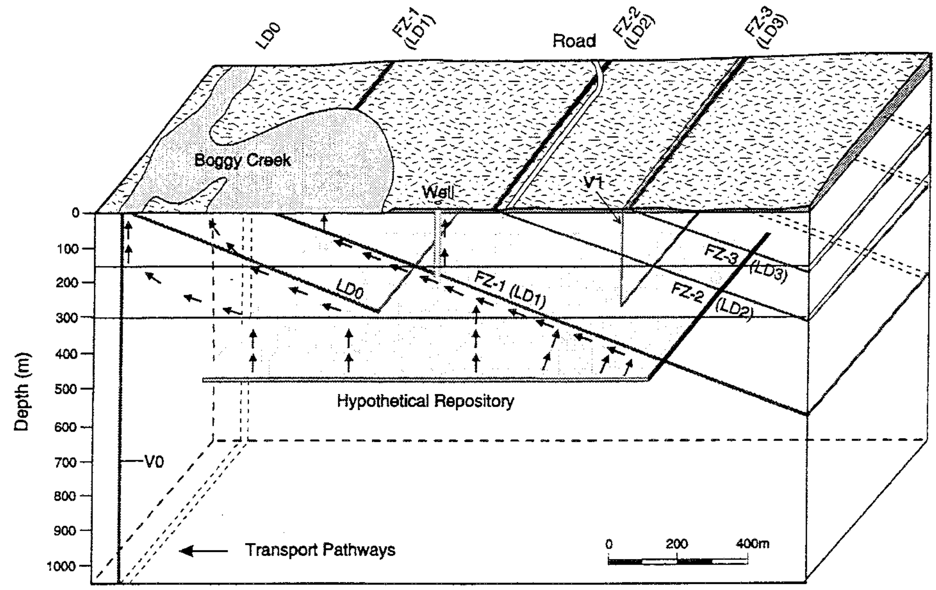


Figure 4-10. Flow Paths from the Hypothetical Repository.

The pathways identified from particle tracking were then simplified into a three-dimensional array of one-dimensional pathway segments (Figure 4-11). This model, called GEONET, was then used as the Geosphere Model in the analysis of the hypothetical disposal system in the case study. Other field and laboratory information from the site investigations (hydraulic, transport and sorption properties, as well as groundwater chemistry and mineralogy) were also incorporated in GEONET.

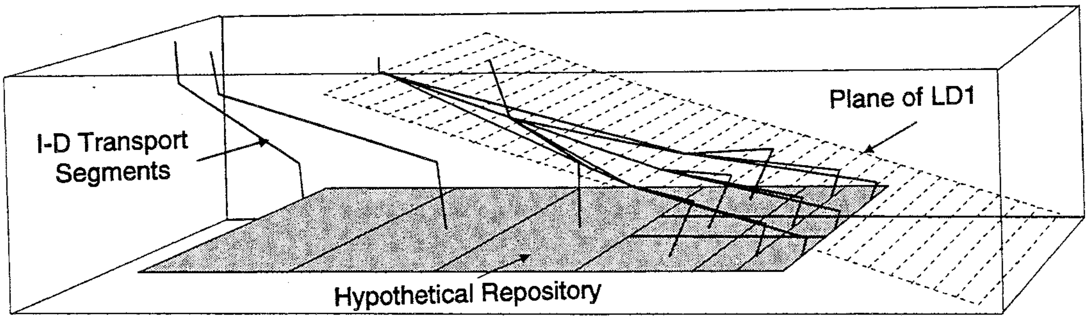


Figure 4-11. Three-Dimensional View of GEONET, the Geosphere Model.

Models used for postclosure assessment would be applicable only for a specific disposal facility design for conditions at a specific site. GEONET was a good representation of transport pathways for contaminant movement from the hypothetical repository to the biosphere in the postclosure assessment case study, however, it would not necessarily be the appropriate code to use to represent transport pathways through the geosphere in a disposal system-model used for postclosure assessment at another site. The appropriateness of the models would need to be justified at each site.

5 EXPERIENCE AND LESSONS LEARNED

5.1 RECONNAISSANCE METHODS

Integrated interpretation of satellite imagery, aerial photographs, and reconnaissance geophysical surveys combined with reconnaissance geological mapping, provides a great deal of information on the shape, size, structure, lithology and geologic setting of plutonic rock bodies in Canadian Shield terrains. The remote reconnaissance methods allow ground based data to be extended to areas not investigated during mapping and permit the identification of features too large to be recognized during ground-based mapping.

Because they provide extensive areal coverage at relatively low cost, maximum use should be made of satellite imagery, aerial photographs, and airborne geophysical surveys in interpreting conditions at sites and preparing base maps and imagery for use in mapping, before beginning detailed ground surveys, mapping, and drilling of cored boreholes.

Aeromagnetic and gravity surveys provide a good indication of major lithological changes and structural features as well as of the heterogeneity and structural fabric of the rock.

5.2 DETAILED SURFACE METHODS

The following surface geophysical survey methods are useful in characterizing various aspects of surface and subsurface geological conditions in plutonic rocks: radar, sonar, VLF-EM tilt angle, VLF-EM resistivity, magnetic, gradient-configuration resistivity and Schlumberger resistivity.

Radar is particularly useful in determining the orientation of fracture zones within 80 m of surface on outcrop as an aid in selecting targets for borehole drilling. Sonar is useful in determining both lake bottom topography and lake sediment thickness. Combining sonar surveys with surveys using lake bottom geochemical probes and helium gas sampling shows promise for locating potential discharge locations of deep groundwater into lake bottoms. VLF-EM is particularly useful in estimating the thickness of overburden.

Seismic reflection surveys show potential for identifying low-dip fracture zones as reflectors to depths of 500 m, although the interpretation of the data is sometimes inconclusive.

In general, where highly conductive overburden materials are present, most electrical-based geophysical methods (magnetotelluric, magnetometric resistivity, and moving electrode resistivity methods) are unable to identify lithologic or structural heterogeneities in the rock. These methods might be more useful at sites with non-conductive overburden or extensive outcrop.

The usefulness of the deep electrical survey methods (TDEM, CSAMT, AMT, MT) during site screening is doubtful because of the lack of field information on the nature of the features identified in the surveys and the poor resolution to a depth of 1000 m in comparison to the other methods available for site screening.

Geological mapping combined with collecting samples for laboratory testing and analysis and evaluation of surface stress indicators provides a good initial indication of the litho-structural domains and the in situ stresses near surface. Radiogenic isotope studies can also be very helpful in establishing the age of pluton formation and the subsequent ages of fracturing, faulting and associated alteration events.

Observations of topographic variations, drainage patterns, and vegetation patterns combined with sampling of springs, seeps, and surface waters provides a good initial indication of the distribution of potential areas of groundwater recharge and discharge.

5.3 BOREHOLE METHODS

AECL has over fifteen years experience with drilling inclined cored boreholes, all using commercial drilling rigs and crews from contractors in the mining exploration industry. The main learning curve for contractors has involved getting an optimized diamond bit design for each different field research area and getting the drillers used to the idea of using clean drill pipe and drilling without drill-fluid additives and without grease on the drill pipe joints. There has been no difficulty obtaining qualified and cost effective diamond-drilling contractors in Canada.

NQ-3 triple tube wireline coring equipment (76 mm diameter borehole and 45 mm diameter core) provides excellent core quality and core recovery (>99%). Losses commonly occur only in rubble zones, where the drilling process can wash out fines. Sometimes it is necessary to start drilling at HQ size (96 mm hole, 61 mm core) or larger, for example when overcore stress measurements are to be done, when a significant length of surface casing is to be used, or when large diameter water pumps are to be used for hydrogeologic testing. The NQ-3 borehole diameter is large enough to allow the use of commercially available slimhole logging probes for a full suite of geophysical logs (spontaneous potential, single point resistance, 16" normal resistivity, natural gamma, gamma-gamma (density), neutron (porosity), full wave-form acoustic (velocity and amplitude), fluid resistivity, temperature, caliper, impeller flowmeter, acoustic televiewer, and borehole television).

AECL normally drills inclined boreholes to facilitate orientation of the core. Usually drilling begins at an angle of 75°, with the expectation that the borehole will deviate naturally to about 55° by completion (for a 1200 m long borehole). Stabilizers are used on the core barrel to control the deviation. Boreholes have been started at as shallow an inclination as 55° with continued deviation to about 35°. However, it becomes difficult to do logging and testing in the boreholes and to install and maintain monitoring systems when significant portions of the borehole are inclined at <45°.

When drilling, the only additive allowed is a drill fluid tracer. The only exception is when drilling the portion of a borehole that is to be cased, where use of an additive would not normally cause contamination of groundwater samples taken from the borehole after it was cased. Not using additives seldom causes drilling problems, except in unconsolidated overburden, which would normally have casing set through it.

The primary advantages of inclined cored boreholes are the better sampling of high-dip features (faults, fractures, foliation, etc.) and the ability to orient the core at the borehole site using gravity based modified Craelius core orientators. Obtaining continuously oriented core on site allows the preparation of an essentially complete log of structural features and general lithology of the core during drilling. Having such a log immediately greatly assists in planning the borehole logging and testing that begin as soon as the drilling is complete and in modifying the location and design of the next borehole to be drilled if necessary.

The geophysical, thermal, fluid conductivity and impeller flowmeter logs generally provide sufficient information to identify potentially permeable intervals or inflows for subsequent testing and monitoring.

Borehole characterization is essential. However, so long as a borehole remains open, the hydrogeological and hydrogeochemical regime is being disturbed, not only in the borehole, but also throughout large volumes of the rock at the site. These disturbances take a long time to stabilize and can delay or even prevent obtaining an understanding of the natural (undisturbed) conditions. Hydraulic head and groundwater chemistry information need to be obtained from intervals in boreholes that are isolated to prevent variations as a result of mixing and interaction within the borehole between different hydrogeological units. Moreover, both hydraulic head and chemistry vary naturally and would also be affected by construction of a repository. Consequently, long term access to the intervals would be essential for monitoring the natural variation and observing any effects caused by the repository. Some form of semi-permanent monitoring instrumentation would be essential to provide both isolation of and long-term access to monitoring intervals in any investigation borehole at a repository site. Any borehole that was not instrumented in such a manner should be completely sealed. Instrumentation or sealing should be done as soon as possible after drilling, consistent with the planned open borehole testing program, to minimize, to the extent possible, the uncontrolled disturbance to the natural groundwater regime. In situations where open borehole testing is planned for later in the site investigation program, the different permeable intervals in the borehole should be isolated by removable temporary packers.

Single borehole hydrogeological testing provides point values of hydrogeological properties. However, knowledge is needed of the continuity of permeability between the boreholes in order to develop an understanding of the distribution of the permeability at the site. In AECL's experience, interpretation of hydraulic interference tests and of long-term records of the hydraulic head in isolated monitoring intervals in boreholes is the best method for developing an understanding of the permeability conditions between clusters of boreholes at a single grid area and between boreholes at adjacent grid areas. Consequently, testing in open boreholes is minimized and hydrogeological monitoring instrumentation is installed as soon as possible. The information obtained by monitoring the hydraulic disturbance caused by drilling subsequent boreholes (each borehole effectively providing a multiple borehole interference test) more than offsets the loss of any information that would have been obtained by more extensive open borehole testing.

From a hydrogeochemical point of view, various methods of identifying and removing drill-water contamination in groundwater from permeable zones have been tested. Use of natural isotopic tracers (^{2}H, ^{3}H, ^{18}O) coupled with obtaining a stable groundwater composition during pumping have been found to give better results and require less monitoring effort, than the addition of a man-made drill-water tracer. Similarly, attempts at measuring electrode parameters (Eh, pH) downhole have indicated that surface measurements in a sealed flow-cell, while subject to more interferences, may still give useful information in most situations and require considerably less equipment, maintenance support, and monitoring effort. In any case, when the groundwater being sampled contains only minor amounts of redox-sensitive species (typically <0.5 mg/L Fe), the interpretation of an electrode-measured Eh is questionable from a thermodynamic standpoint. Whether the measured value is from a surface or a downhole sensor becomes irrelevant. Most groundwaters we have sampled on the Canadian Shield contain <0.5 mg/L Fe and higher concentrations have usually been found to be indicative of contamination from the drilling process or from iron in the temporary casing systems or sampling systems. Recently, we have found that microbiological activity is enhanced in and adjacent to a borehole and sampling without adequate flushing leads to erroneous hydrogeochemical results (Stroes-Gascoyne et al. 1993). This supports our previous practice of flushing, monitoring, and final sampling.

5.4 INTEGRATION OF DATA AND INTERPRETATION

The concept of domains (volumes of rock with significantly different litho-structural, hydrogeological, geochemical, or geomechanical characteristics) provides a very useful framework for the interpretation of site conditions and the integration of site data. The primary objective of the interpretation is the three-dimensional delineation of the pathways for groundwater flow and contaminant transport and the characterization of the potential for contaminant retardation along the pathways.

Point measurements of rock properties (permeability, porosity, etc.) and geochemical conditions (mineralogy, groundwater chemistry, etc.) in outcrop or in boreholes are, by themselves, of limited usefulness in understanding site conditions. The point measurements need to be related to hypotheses that can explain the observed distributions of values as well as enable the formulation of testable predictions of the properties or conditions away from the boreholes.

We have found the litho-structural domain to be a very useful link between hypotheses regarding the origin of features with particular properties, the expected geometric distribution of the feature, and the expected variability in the properties associated with the feature. Because the litho-structural domain is related to an interpretation of the origin and subsequent deformational history of the plutonic rock at the site, it has a regional context that allows predictions to be made about its geometric distribution and continuity and the variability and heterogeneity of its properties. Because the domain incorporates both lithological characteristics and structural characteristics, it provides a framework for distinguishing the other domains of primary interest (the hydrogeological, geochemical, and geomechanical domains).

In our judgement, the integrated conceptual model of the site should be the focus of data integration and interpretation. Initially, potential locations of the repository would be considered in the context of this model. Subsequently, potential locations of disposal areas in the repository would be considered. Surface-based site investigations would be focussed on reducing uncertainties about the geometry of the features in this model and about the variability and heterogeneity of the properties of the features. The mathematical models representing this conceptual model would be used to identify locations where the long term effects of disposal might be particularly sensitive to variations in the properties of the features. New information would be evaluated for consistency with the model, either confirming the features or characteristics or requiring their modification.

In our experience, interpreting the data within the context of an integrated conceptual model quickly highlights anomalous observations. Additional investigations can then be undertaken to determine if the observation is valid. If it is, then the model must be modified where necessary to be consistent with the new understanding of the conditions at the site.

5.5 THE OBSERVATIONAL METHOD AND TESTING HYPOTHESES

Site investigations for a repository would include gathering data on the rock mass and groundwater systems at the site. However, before excavation began it would not be possible to identify all the details of local variability important for design and assessment. This initial lack of details about local variability within a selected rock mass is common in underground construction of projects such as underground powerhouses and storage chambers and rail and highway tunnels.

Successful construction of such projects has been largely the result of a design approach that accommodates observations made as construction progresses.

We applied this "observational method" (Peck 1969) during the design and construction of the Underground Research Laboratory, and we found it to be a valuable approach for the integration of site investigations, conceptual model development, and the planning and design process. This approach underlies the iterative process of integrating the information from the site into a hypothesis represented by a conceptual model, identifying areas where information is needed (or predicting conditions that will be encountered), conducting additional site investigations, re-evaluating the model in light of the new information, and then beginning the cycle again.

6. RECENT DEVELOPMENTS

6.1 IMAGE ANALYSIS AND GIS

Recent advances in personal computer technology now enable geologists to work directly with spectral data from satellites using desktop facilities. Previously, only specialized facilities, such as those at the Canada Centre for Remote Sensing and other similar provincial organizations, were available for manipulating these large digital spectral data sets in Canada. AECL has recently acquired the computer capabilities to manipulate these types of data sets and we have developed a simple set of lineament identification rules. These rules can be easily modified for the conditions existing in any particular area and can be adapted for the type of lineament information that is available. AECL is now developing procedures for rapidly integrating the information from satellite imagery with geological, geophysical, and geographic information to produce maps and to aid in interpreting conditions at a site.

6.2 SATELLITE AND AIRBORNE RADAR IMAGERY

The development of synthetic aperture radar (SAR) satellite sensors has greatly enhanced our ability to perform geological analysis of structural and lithological conditions of an area using satellite imagery. AECL has recently obtained airborne radar survey data in conjunction with ground truth data at the Whiteshell Research Area to evaluate the usefulness of SAR as a reconnaissance method and to compare with the satellite data. Initial inspection of the airborne data suggests that this method will be an important addition to the vertical magnetic gradient survey for reconnaissance identification of potentially important linear features for subsequent evaluation by detailed investigations.

6.3 ANALYSIS OF CROSS-HOLE RADAR AND SEISMIC DATA

Analysis of cross-hole radar and seismic data has concentrated on the transmission characteristics and the preparation of tomograms based on the transit times of the transmitted signals. However, the data contain information about the signal amplitude and its attenuation that should also be useful for analysis. There should also be signals that have been reflected from features in the survey space that could provide useful information for interpretation. AECL is considering ways in which this other information in the data sets could be extracted and used to supplement the current tomographic analysis.

6.4 IN SITU LEACHING EXPERIMENTS

AECL is conducting long-term in situ leaching experiments at the URL to investigate the usefulness of borehole leach tests for:

- determining the contribution of pore fluids to the chemistry of groundwater in granite, and
- determining the in situ porosity and permeability of the rock matrix.

Borehole test intervals have been isolated in unfractured rock. The intervals are far enough from the access tunnels for the test area to be beyond the effect of stress redistribution. The test intervals are aligned both parallel to the foliation in the rock and perpendicular to it. The intervals are filled with deionized water and sampled periodically to monitor the increase in salinity. Results are being evaluated in conjunction with information about the chemistry of fluid inclusions, grain boundary pore water, crushed rock leachate, and groundwater from the fracture zones at the URL.

6.5 CADD MODELLING

A computer-aided design and drafting (CADD) system has been implemented at the URL. Databases of spatially located information from boreholes, geologic mapping, geophysical surveys, acoustic emission/microseismic monitoring, excavation surveys, and rock property testing have been developed and are maintained by the system. The system is used for production of perspective views, maps, plans, and cross-sections of the geology and excavations of any portion of the URL and for statistical analysis of the rock properties or characteristics.

Working with three-dimensional perspective views that can be rotated in a CADD environment makes it easier

- to visualize the extrapolation of lithologic and structural features between the boreholes that have intersected them,
- to evaluate the reasonableness of alternative interpretations and correlations, and
- to identify relationships between variations in rock mass properties (such as permeability) and lithological or structural features.

Conceptual models of the site developed with the aid of a CADD system can more readily incorporate the geometric complexity of the lithostructural, geomechanical, hydrogeological, and geochemical domains than can manually drawn two-dimensional or physically constructed three-dimensional models. Consequently, more of the three-dimensional volumetric relationships can be kept in mind and in view as decisions are made in developing the integrated model of the hydrogeological units at the site, and the mathematical representations for groundwater flow and contaminant transport. The models in the CADD system are also easier and quicker to modify as new information becomes available.

6.6 ELECTRON SPIN RESONANCE ANALYSIS

Analysis of charges trapped in the crystal lattice of quartz from fault gouge using electron spin resonance may provide information on the age of the most recent movement on a fault. Previously, ages from this method tended to be overestimated, which would limit the usefulness of the method for determining when the most recent movement might have been and thus the likelihood that a fault was potentially active. New developments appear to have overcome this limitation and the method is being tested on samples from Fracture Zone 2 at the URL.

7. CONCLUSIONS

AECL has concluded that the surface-based methods for site investigations that have been developed and demonstrated in the field and in the laboratory are sufficient for the initial siting of a repository in plutonic rock. The methods can provide the geotechnical information needed to select candidate sites and the locations for exploratory shafts at those sites. Methods are also available for integrating the information from site investigations in conceptual and mathematical models that would be used to help in evaluating the long-term performance and environmental effects of a repository at a plutonic rock site and in making the decision whether to proceed with exploratory excavations. Although they are not discussed in this report, methods have also been developed and demonstrated for underground site investigations.

After more than fifteen years of research, development, and demonstration, it is AECL's judgement that existing methods for both surface-based and underground site investigations are adequate for obtaining the information needed to site and design a repository for the safe disposal of nuclear fuel waste in plutonic rock and to assess the safety of the disposal system and its potential environmental effects in comparison with current Canadian regulatory standards.

Borehole investigations would be an essential part of the site investigations. The number of boreholes required would depend on the geologic complexity of the candidate area and on how predictable the subsurface conditions turned out to be. Regardless of the complexity, several grid areas and a significant number of boreholes would be required.

The success of the URL Drawdown Experiment in both modelling and monitoring the disturbance caused by initial shaft sinking at the URL demonstrated:

- that field data from surface-based site investigations can be incorporated into conceptual and mathematical models;
- that the models can represent the conditions at a site and the groundwater flow in fractured plutonic rock at a scale adequate for siting and designing a repository and for assessing its performance; and
- that the porous media equivalent modelling approach can adequately describe the hydraulic properties of the fractured rock mass, so long as the location, geometry and spatial variability of the hydraulic properties of the fracture zones are treated discretely in the models.

The site investigations at AECL's field research areas, including the URL, have provided important demonstrations of the reliability and usefulness of many of the detailed surface-based site investigation methods that would be used to characterize and model groundwater flow and solute transport conditions at a repository site in plutonic rock.

On the basis of the experience gained from these investigations, AECL considers use of an observational approach to be essential during the site investigations and during the design, construction, and operation of the underground components of a repository.

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List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

1992
TR 92-46
SKB Annual Report 1992
Including Summaries of Technical Reports Issued during 1992
Stockholm, May 1993

Technical Reports
List of SKB Technical Reports 1994

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N Platts, D J Blackwood, C C Naish
AEA Technology, UK
February 1994

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Paul Wersin, Kastriot Spahiu, Jordi Bruno
MBT Technología Ambiental, Cerdanyola, Spain
February 1994

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Reassessment of seismic reflection data from the Finnsjön study site and prospectives for future surveys
Calin Cosma[1], Christopher Juhlin[2], Olle Olsson[3]
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[3] Conterra AB, Uppsala, Sweden
February 1994

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May 1994

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[2] Terralogica AB
November 1993

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Swedish Nuclear Fuel & Waste Management Co, SKB
January 1994

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January 1994

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May 1994

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June 1994

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June 1994

TR 94-11
Äspö Hard Rock Laboratory Annual Report 1993
SKB
June 1994

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January 1994

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A R Hoch, S M Sharland
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January 1994

TR 94-16
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Robert J Finch[2], Rodney C Ewing[2]
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October 1994

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Antti Öhberg[1], Pauli Saksa[2], Henry Ahokas[2],
Paula Ruotsalainen[2], Margit Snellman[3]
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May 1994