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The Disposal of Canada's Nuclear Fuel Waste: Site Screening and Site Evaluation Technology

Le stockage permanent des déchets de combustible nucléaire du Canada : Identification d'endroits possibles et technique d'évaluation d'un site possible

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SITE SCREENING AND SITE EVALUATION TECHNOLOGY

by

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Pinawa, Manitoba ROE 1L0
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LE STOCKAGE PERMANENT DES DÉCHETS DE COMBUSTIBLE NUCLÉAIRE DU CANADA : IDENTIFICATION D'ENDROITS POSSIBLES ET TECHNIQUE D'ÉVALUATION D'UN SITE POSSIBLE

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RÉSUMÉ

Le concept de stockage permanent des déchets de combustible du Canada consiste à stocker de façon permanente les déchets dans une installation souterraine construite à une profondeur nominale de 500 à 1 000 m, sur un site approprié faisant partie de la formation de roche plutonique du Bouclier canadien. EACL documentera la possibilité de réalisation de ce concept ainsi que les évaluations de son impact sur l'environnement et la santé humaine dans une Étude d'impact sur l'environnement (EIE). Ce rapport est l'un d'une série de neuf documents de référence principaux de l'EIE. Il décrit l'approche et les méthodes qu'on emploierait au cours de l'opération de sélection éventuelle d'un site du projet de stockage permanent pour identifier un site possible préféré de stockage permanent et pour confirmer sa convenance à la construction d'une installation de stockage permanent.

L'opération de sélection éventuelle d'un site se divise en deux sous-opérations distinctes mais étroitement liées, l'identification d'endroits possibles et l'évaluation d'un site possible. L'identification d'endroits possibles comprendrait principalement des opérations d'exploration de régions à sites possibles du Bouclier pour identifier des endroits qui pourraient exister et convenir à la construction d'une installation souterraine; elle permettrait d'identifier un petit nombre d'endroits possibles où davantage d'opérations d'exploration minutieuses se justifieraient. L'évaluation d'un site possible comprendrait des études de plus en plus minutieuses à la surface et sous la surface des endroits possibles pour d'abord identifier des endroits qui pourraient convenir parmi les endroits possibles et ensuite caractériser ces sites possibles de stockage permanent et permettre ainsi d'identifer l'endroit possible préféré pour construire l'installation souterraine de stockage permanent. L'évaluation du site se terminerait par la construction de puits et de galeries d'exploration à l'endroit préféré pour la construction de l'installation souterraine et la caractérisation du sous-sol s'effectuerait pour confirmer la convenance de l'endroit possible préféré.

On mettrait en oeuvre un programme intégré d'opérations de recherche géologique, géophysique, hydrogéologique, géochimique et géomécanique pour obtenir les renseignements géoscientifiques nécessaires à l'évaluation de la convenance d'endroits à sites possibles et de sites possibles à l'implantation d'une installation souterraine de stockage permanent. On caractériserait minutieusement les endroits à sites possibles et les sites possibles d'installation souterraine de stockage permanent pour comprendre le régime d'écoulement d'eaux souterraines dans la roche. La compréhension de ce régime servirait à disposer l'installation souterraine de stockage permanent dans la roche de sorte à permettre à l'écoulement et aux caractéristiques chimiques des eaux souterraines d'accroître la sûreté du système de stockage permanent.

EACL a mis au point et éprouvé les méthodes géoscientifiques de caractérisation des conditions régnant dans la roche plutonique du Bouclier canadien aux aires de recherches géologiques qu'il a établies sur celui-ci. Dans ce rapport, on présente des exemples de méthodes de caractérisation de site qui sont tirés des études effectuées à ces aires de recherches. Les travaux géoscientifique exécutés à l'Aire de recherche de Whiteshell (ARW) de la partie du Bouclier située dans le sud-est du Manitoba illustre de très près l'espace physique couvert par la caractérisation, lequel serait nécessaire pour la sélection éventuelle d'un site d'installation souterraine réelle de stockage de déchets de combustible nucléaire dans un endroit possible du Bouclier. Les travaux de caractérisation effectués au site du Laboratoire de recherches souterrain (LRS) de ARW montrent comment évaluer les conditions géoscientifiques de la roche à un site possible de stockage permanent et illustrent comment on se servirait des renseignements pour confirmer la convenance du site au stockage permanent.

Dans ce rapport, on présente également des preuves, d'après des études de cas effectuées au LRS et aux aires de recherches géologiques, que les méthodes de caractérisation de site par la surface, par les trous de forage et par le sous-sol, mises au point par EACL le sont maintenant suffisamment pour qu'on puisse les employer de manière à obtenir les renseignements géoscientifiques à la sélection d'un site d'installation souterraine de stockage permanent dans la roche plutonique du Bouclier canadien. Nous pensons qu'on continuera à améliorer ces méthodes de caractérisation de site et qu'on mettra au point des nouvelles méthodes au cours de la longue période nécessaire pour mettre en oeuvre le projet de stockage permanent. On continue à apporter des améliorations et à réaliser des nouveaux progrès par la recherche courante et continue au site du LRS et aux autres aires de recherches géologiques établies sur le Bouclier. Toutefois, les méthodes dont on dispose actuellement sont suffisamment bien mises au point pour permettre de commencer la sélection d'un site.

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ABSTRACT

The concept for the disposal of Canada's nuclear fuel waste is to dispose of the waste in an underground vault, nominally at 500 m to 1000 m depth, at a suitable site in plutonic rock of the Canadian Shield. The feasibility of this concept and assessments of its impact on the environment and human health, will be documented by AECL in an Environmental Impact Statement (EIS). This report is one of nine primary references for the EIS. It describes the approach and methods that would be used during the siting stage of the disposal project to identify a preferred candidate disposal site and to confirm its suitability for constructing a disposal facility.

The siting stage is divided into two distinct but closely related substages, site screening and site evaluation. Site screening would mainly involve reconnaissance investigations of siting regions of the Shield to identify potential candidate areas where suitable vault locations are likely to exist. Site screening would identify a small number of candidate areas where further detailed investigations were warranted. Site evaluation would involve progressively more detailed surface and subsurface investigations of the candidate areas to first identify potentially suitable vault locations within the candidate areas, and then characterize these potential disposal sites to identify the preferred candidate location for constructing the disposal vault. Site evaluation would conclude with the construction of exploratory shafts and tunnels at the preferred vault location, and underground characterization would be done to confirm the suitability of the preferred candidate site.

An integrated program of geological, geophysical, hydrogeological, geochemical and geomechanical investigations would be implemented to obtain the geoscience information needed to assess the suitability of the candidate siting areas and candidate sites for locating a disposal vault. The candidate siting areas and candidate disposal vault sites would be carefully characterized to understand the groundwater flow conditions in the rock. This understanding would be used to situate the disposal vault in the rock so as to allow the flow and chemical characteristics of the groundwater to enhance the safety of the disposal system.

The geoscience methods for characterizing the conditions within plutonic rocks of the Canadian Shield have been developed and tested by AECL at geologic research areas on the Shield. This report presents examples of the site characterization methods which are drawn from the studies at these research areas. The geoscience work performed at the Whiteshell Research Area (WRA) on the Shield in southeastern Manitoba comes closest to illustrating the spatial coverage of characterization that would be required for siting an actual nuclear fuel waste disposal vault in a candidate area of the Shield. The characterization work done at the site of the Underground Research Laboratory (URL) in the WRA demonstrates how to evaluate the geoscience conditions of the rock at a candidate disposal site, and illustrates how that information would be used to confirm the suitability of the site for disposal.

This report presents evidence from case studies at the URL and the geologic research areas that the surface-based, borehole and underground site characterization methods developed by AECL are now sufficiently developed that they can be used to obtain the geoscience information needed for siting a disposal vault in plutonic rock of the Canadian Shield. We expect that these site characterization methods will continue to be improved and that new methods will be developed during the long time period required for implementation of the disposal project. Improvements and new developments are continuing through ongoing research at the site of the URL and at the other geologic research areas on the Shield. However the methods that are currently available are sufficiently well developed to allow siting to commence.

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PREFACE

In 1992, 15% of the electricity generated in Canada was produced using CANDU nuclear reactors. A by-product of the nuclear power is used CANDU fuel, which consists of ceramic uranium dioxide pellets and metal structural components. Used fuel is highly radioactive. The used fuel from Canada's power reactors is currently stored in water-filled pools or dry storage concrete containers. Humans and other living organisms are protected by isolating the used fuel from the natural environment and by surrounding it with shielding material. Current storage practices have an excellent safety record.

At present, used CANDU fuel is not reprocessed. It could, however, be reprocessed to extract useful material for recycling, and the highly radioactive material that remained could be incorporated into a solid. The term "nuclear fuel waste," as used by AECL, refers to either

- the used fuel, if it is not reprocessed, or
- a solid incorporating the highly radioactive waste from reprocessing.

Current storage practices, while safe, require continuing institutional controls such as security measures, monitoring, and maintenance. Thus storage is an effective interim measure for protection of human health and the natural environment but not a permanent solution. A permanent solution is disposal, a method "in which there is no intention of retrieval and which, ideally, uses techniques and designs that do not rely for their success on long-term institutional control beyond a reasonable period of time" (AECB 1987a).

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. AECL was made responsible for research and development on "... disposal in a deep underground repository in intrusive igneous rock" (Joint Statement 1978). Ontario Hydro was made responsible for studies on interim storage and transportation of used fuel and has contributed to the research and development on disposal. Over the years a number of other organizations have also contributed to the Program, including Energy, Mines and Resources Canada; Environment Canada; universities; and companies in the private sector.

The disposal concept is to place the waste in long-lived containers; emplace the containers, enveloped by sealing materials, in a disposal vault excavated at a nominal depth of 500 to 1000 m in intrusive igneous (plutonic) rock of the Canadian Shield; and (eventually) seal all excavated openings and exploration boreholes to form a passively safe system. Thus there would be multiple barriers to protect humans and the natural environment from contaminants in the waste: the container, the very low-solubility waste form, the vault seals, and the geosphere. The disposal technology includes options for the design of the engineered components, including the disposal container, disposal vault, and vault seals, so that it is adaptable to a wide range of regulatory standards, physical conditions, and social requirements. Potentially suitable bodies of plutonic rock occur in a large number of locations across the Canadian Shield.

In developing and assessing this disposal concept, AECL has consulted broadly with members of Canadian society to help ensure that the concept and the way in which it would be implemented are technically sound and represent a generally acceptable disposal strategy. Many groups in Canada have had opportunities to comment on the disposal concept and on the waste management program. These include government departments and agencies, scientists, engineers, sociologists, ethicists, and other members of the public. The Technical Advisory Committee to AECL on the Nuclear Fuel Waste Management Program, whose members are nominated by Canadian scientific and engineering societies, has been a major source of technical advice.

In 1981, the governments of Canada and Ontario announced that "... no disposal site selection will be undertaken until after the concept has been accepted. This decision also means that the responsibility for disposal site selection and subsequent operation need not be allocated until after concept acceptance" (Joint Statement 1981).

The acceptability of the disposal concept is now being reviewed by a federal Environmental Assessment Panel, which is also responsible for examining a broad range of issues related to nuclear fuel waste management (Minister of the Environment, Canada 1989). After consulting the public, the Panel issued guidelines to identify the information that should be provided by AECL, the proponent of the disposal concept (Federal Environmental Assessment Review Panel 1992).

AECL is preparing an Environmental Impact Statement to provide information requested by the Panel and to present AECL's case for the acceptability of the disposal concept. A Summary will be issued separately. This report is one of nine primary references that summarize major aspects of the disposal concept and supplement the information in the Environmental Impact Statement. A guide to the contents of the EIS, the Summary, and the primary references follows this Preface.

In accordance with the 1981 Joint Statement of the governments of Canada and Ontario, no site for disposal of nuclear fuel waste is proposed at this time. Thus in developing and assessing the disposal concept, AECL could not design a facility for a proposed site and assess the environmental effects to determine the suitability of the design and the site, as would normally be done for an Environmental Impact Statement. Instead, AECL and Ontario Hydro have specified illustrative "reference" disposal systems and assessed those.

A "reference" disposal system illustrates what a disposal system, including the geosphere and biosphere, might be like. Although it is hypothetical, it is based on information derived from extensive laboratory and field research. Many of the assumptions made are conservative, that is, they would tend to overestimate adverse effects. The technology specified is either available or judged to be readily achievable. A reference disposal system includes one possible choice among the options for such things as the waste form, the disposal container, the vault layout, the vault seals, and the system for transporting nuclear fuel waste to a disposal facility. The components and designs chosen are not presented as ones that are being recommended but rather as ones that illustrate a technically feasible way of implementing the disposal concept.

After the Panel has received the requested information, it will hold public hearings. It will also consider the findings of the Scientific Review Group, which it established to provide a scientific evaluation of the disposal concept. According to the Panel's terms of reference "As a result of this review the Panel will make recommendations to assist the governments of Canada and Ontario in reaching decisions on the acceptability of the disposal concept and on the steps that must be taken to ensure the safe long-term management of nuclear fuel wastes in Canada" (Minister of the Environment, Canada 1989).

Acceptance of the disposal concept at this time would not imply approval of any particular site or facility. If the disposal concept is accepted and implemented, a disposal site would be sought, a disposal facility would be designed specifically for the site that was proposed, and the potential environmental effects of the facility at the proposed site would be assessed. Approvals would be sought in incremental stages, so concept implementation would entail a series of decisions to proceed. Decision-making would be shared by a variety of participants, including the public. In all such decisions, however, safety would be the paramount consideration.

The EIS, Summary, and Primary References

Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste (AECL 1994a)

Summary of the Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste (AECL 1994b)

The Disposal of Canada's Nuclear Fuel Waste: Public Involvement and Social Aspects (Greber et al. 1994)

The Disposal of Canada's Nuclear Fuel Waste: Site Screening and Site Evaluation Technology (Davison et al., this volume)

The Disposal of Canada's Nuclear Fuel Waste: Engineered Barriers Alternatives (Johnson et al. 1994b)

The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility (Simmons and Baumgartner 1994)

The Disposal of Canada's Nuclear Fuel Waste: Preclosure Assessment of a Conceptual System (Grondin et al. 1994)

The Disposal of Canada's Nuclear Fuel Waste: Postclosure Assessment of a Reference System (Goodwin et al. 1994)

The Disposal of Canada's Nuclear Fuel Waste: The Vault Model for Postclosure Assessment (Johnson et al. 1994a)

The Disposal of Canada's Nuclear Fuel Waste: The Geosphere Model for Postclosure Assessment (Davison et al. 1994)

The Disposal of Canada's Nuclear Fuel Waste: The Biosphere Model, BIOTRAC, for Postclosure Assessment (Davis et al. 1993)

GUIDE TO THE CONTENTS OF THE ENVIRONMENTAL IMPACT STATEMENT, THE SUMMARY, AND THE PRIMARY REFERENCES

ENVIRONMENTAL IMPACT STATEMENT AND SUMMARY

Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste (AECL 1994a)

- provides an overview of AECL's case for the acceptability of the disposal concept
- provides information about the following topics:
  - the characteristics of nuclear fuel waste
  - storage and the rationale for disposal
  - major issues in nuclear fuel waste management
  - the disposal concept and implementation activities
  - alternatives to the disposal concept
  - methods and results of the environmental assessments
  - principles and potential measures for managing environmental effects
  - AECL's overall evaluation of the disposal concept

Summary of the Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste (AECL 1994b)

- summarizes the contents of the Environmental Impact Statement

PRIMARY REFERENCES

The Disposal of Canada's Nuclear Fuel Waste: Public Involvement and Social Aspects (Greber et al. 1994)

- describes the activities undertaken to provide information to the public about the Nuclear Fuel Waste Management Program and to obtain public input into the development of the disposal concept
- presents the issues raised by the public and how the issues have been addressed during the development of the disposal concept or how they could be addressed during the implementation of the disposal concept
- discusses social aspects of public perspectives on risk, ethical issues associated with nuclear fuel waste management, and principles for the development of a publicly acceptable site selection process

The Disposal of Canada's Nuclear Fuel Waste: Site Screening and Site Evaluation Technology (this volume)

- discusses geoscience, environmental, and engineering factors that would need to be considered during siting

- describes the methodology for characterization, that is, for obtaining the data about regions, areas, and sites that would be needed for facility design, monitoring, and environmental assessment

<u>The Disposal of Canada's Nuclear Fuel Waste: Engineered Barriers Alternatives (Johnson et al. 1994b)</u>

- describes the characteristics of nuclear fuel waste

- describes the materials that were evaluated for use in engineered barriers, such as containers and vault seals

- describes potential designs for containers and vault seals

- describes procedures and processes that could be used in the production of containers and the emplacement of vault-sealing materials

<u>The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility (Simmons and Baumgartner 1994)</u>

- discusses alternative vault designs and general considerations for engineering a nuclear fuel waste disposal facility

- describes a disposal facility design that was used to assess the technical feasibility, costs, and potential effects of disposal (Different disposal facility designs are possible and might be favoured during concept implementation.)

- presents cost and labour estimates for implementing the design

<u>The Disposal of Canada's Nuclear Fuel Waste: Preclosure Assessment of a Conceptual System (Grondin et al. 1994)</u>

- describes a methodology for estimating effects on human health, the natural environment, and the socio-economic environment that could be associated with siting, constructing, operating (includes transporting used fuel), decommissioning, and closing a disposal facility

- describes an application of this assessment methodology to a reference disposal system (We use the term "reference" to designate the disposal systems, including the facility designs, specified for the assessment studies. Different disposal facility designs are possible and might be favoured during concept implementation.)

- discusses technical and social factors that would need to be considered during siting

- discusses possible measures and approaches for managing environmental effects

The Disposal of Canada's Nuclear Fuel Waste: Postclosure Assessment of a Reference System (Goodwin et al. 1994)

- describes a methodology for
  - estimating the long-term effects of a disposal facility on human health and the natural environment,
  - determining how sensitive the estimated effects are to variations in site characteristics, design parameters, and other factors, and
  - evaluating design constraints

- describes an application of this assessment methodology to a reference disposal system (We use the term "reference" to designate the disposal systems, including the facility designs, specified for the assessment studies. Different disposal facility designs are possible and might be favoured during concept implementation.)

The Disposal of Canada's Nuclear Fuel Waste: The Vault Model for Postclosure Assessment (Johnson et al. 1994a)

- describes the assumptions, data, and model used in the postclosure assessment to analyze processes within and near the buried containers of waste

- discusses the reliability of the data and model

The Disposal of Canada's Nuclear Fuel Waste: The Geosphere Model for Postclosure Assessment (Davison et al. 1994)

- describes the assumptions, data, and models used in the postclosure assessment to analyze processes within the rock in which a disposal vault is excavated

- discusses the reliability of the data and model

The Disposal of Canada's Nuclear Fuel Waste: The Biosphere Model, BIOTRAC, for Postclosure Assessment (Davis et al. 1993)

- describes the assumptions, data, and model used in the postclosure assessment to analyze processes in the near-surface and surface environment

- discusses the reliability of the data and model

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EXECUTIVE SUMMARY

AECL proposes that Canadian nuclear fuel waste be buried in an underground vault at a nominal depth of 500 m to 1000 m in a plutonic rock mass of the Canadian Shield. The disposal vault would incorporate multiple engineered barriers to isolate the waste from the near-field conditions in the rock. The candidate areas and sites for the vault location would be carefully characterized to understand the groundwater flow conditions in the rock. This knowledge would be used to select a preferred vault location and engineering designs that would act together to delay and impede the movement of vault contaminants through the rock to the human and natural surface environment, after the vault has been closed. The vault and waste emplacement rooms would be situated in the rock so as to allow the flow and chemical characteristics of the groundwater to enhance the safety of the disposal system.

Siting is the first stage of the overall waste disposal project; construction, operation, decommissioning, closure, and any periods of long term environmental and performance monitoring would follow. Siting is the process of choosing a suitable site for the location of the disposal vault.

The siting process will consider a wide range of technical, social, environmental and economic factors. This report deals mainly with the technical factors that need to be considered in siting, and in particular it focuses on those geoscience factors that will largely determine the suitability of a site for locating and constructing a disposal vault. Social and economic aspects of siting and the overall siting process are dealt with in other reports of this series (Grondin et al. 1994, Greber et al. 1994, and AECL 1994a).

The siting stage is expected to take at least 20 years and has been separated into two distinct but closely related substages, site screening and site evaluation. Site screening would mainly involve reconnaissance investigations and an examination of existing information for siting regions, to identify relatively large potential candidate areas where suitable vault locations are likely to exist. Site screening would end with recommendations on whether to proceed with further detailed investigations of a small number of candidate areas and potential vault locations. Site evaluation would involve progressively more detailed surface and subsurface investigations of these relatively large candidate areas (about 400 km^2 in size) to narrow the geographic focus to smaller potential vault sites (about 25 km^2 in size) and finally to the preferred candidate vault location (about 5 km^2) for the construction and operation of the disposal vault.

An integrated program of geologic, geophysical, hydrogeological, geochemical and geomechanical investigations would be used during site evaluation to obtain the necessary geoscience information to assess the suitability of these candidate areas, potential vault locations and candidate sites. Particular attention would be given to performing tests and observations in networks of deep boreholes to develop an

understanding of the groundwater conditions at the candidate areas and sites.

Site evaluation would include locating and constructing exploratory shafts and tunnels at the preferred candidate vault site and performing underground characterization activities in these excavations. Although the siting stage of the project would stop after the exploratory underground excavation was completed and construction of the facilities for nuclear fuel waste disposal began, many of the surface and underground site characterization activities that were begun during siting would continue throughout the construction, operation, decommissioning and closure stages of the project.

The disposal vault would be constructed at a site which is thoroughly characterized and is carefully located in a suitable regional geologic and hydrogeologic setting. This knowledge will be used to situate and design the vault within the groundwater flow systems so as to delay and impede the release and migration of vault contaminants to the surface environment. This will initially involve a thorough evaluation of the surface and subsurface conditions of a relatively large candidate area (at least 400 km^2) surrounding potentially suitable vault locations. A patchwork of grid areas (each nominally 1-2 km^2), where detailed surface observations are made, and networks of boreholes are drilled, tested and monitored, would provide the information necessary to establish this larger scale understanding for the candidate areas. Furthermore, geoscience conditions of the preferred site selected for the location of the disposal vault (nominally about 25 km^2) would be thoroughly characterized, first using surface-based methods and networks of boreholes at the site, and then using underground methods in exploratory shafts and tunnels at the preferred vault location (nominally about 5 km^2). This will provide the information needed to prepare vault layout and waste placement plans that account for site specific conditions and accommodate any future changes that might be anticipated in these conditions.

A major emphasis in the site evaluation approach is on developing an understanding of the groundwater conditions in the rock at the disposal vault site and establishing how these conditions relate to the larger scale groundwater conditions of the rocks in the surrounding candidate area. AECL has been developing and testing geoscience methods for screening and evaluating plutonic rocks of the Canadian Shield for siting a nuclear fuel waste disposal vault since 1975. Four main geologic research areas on the Canadian Shield have been used for this purpose: two located in granitic plutons (one near Atikokan in northwestern Ontario and one near Pinawa in southeastern Manitoba); one on a gabbroic pluton (near Massey in central Ontario); and one on gneissic terrain (near Chalk River in eastern Ontario). Other regional geologic studies have also been conducted in northwestern Ontario to supplement the studies at the geologic research areas. The main objective for the development of these site screening and site evaluation methods has been to obtain information on the factors that govern the rate of groundwater movement through the rock, in particular the degree and style of fracturing in the rock, the permeability and porosity conditions within the fractures, and how the fractures interconnect with each other and to the surface. Examples from work done at the various geologic research areas illustrate the different technologies that can be used for obtaining this information during site screening and site evaluation. Airborne, surface, borehole and underground methods are currently available to provide the geoscience information required for the various size scales of site characterization during siting (candidate areas of at least 400 km^2, candidate sites of nominally 25 km^2, and the vault site of nominally 5 km^2).

The field investigations at the geologic research areas on plutonic rocks of the Shield have shown that the degree of fracturing in the rock, its spatial arrangement and interconnections to the surface topography, has a strong effect in controlling the rate and direction of movement and the chemical compositions of the groundwater in the rock at the proposed disposal vault depths (500-1000 m). Characterization during site screening would identify features at surface that might indicate the presence of fracture zones in the rock and would determine the potential size and hydrogeologic characteristics of the blocks or volumes of rock bounded by them. Characterization during site evaluation would identify the significant zones of different lithologies, identify the fracture zones, determine their positions throughout the rock mass and their positions with respect to each other and the surface topography, determine the hydrogeologic and geochemical properties associated with them that would affect the movement of contaminants from disposal vault depths, and determine the fracture domains and contaminant transport properties of the blocks of rock bounded by them.

In general terms three main fracture domains can be distinguished in plutonic rocks of the Shield which relate to the degree of fracturing:

- fracture zones (faults), which are volumes of intensely fractured rock; usually these can have significant internal variability of solute transport properties such as permeability and porosity;

- moderately fractured rock, which is a volume of rock containing a small number of sets of relatively widely spaced, interconnected discrete fractures or joints (moderately fractured rock can have high or low permeability depending on the openess and degree of inerconnection of the fractures) and;

- sparsely fractured rock, which is volume of rock containing microcracks and very sparsely distributed discrete fractures that are not very interconnected (sparsely fractured rock has fairly uniform solute transport properties and low permeability).

Although these domains are readily recognizable in boreholes drilled into the rock and in underground excavations, the contacts between them may be gradational and there can be significant differences among them in terms of the degree of internal variability of their hydrogeologic and solute transport properties.

The most important pathways for the movement of groundwater in plutonic rock bodies at the depths of a proposed disposal vault are discrete zones of intense fracturing that cut through the rock and are continuous over relatively large distances. This intense fracturing is concentrated in widely-spaced, narrow fault zones of usually only a few metres thickness. These zones may extend for distances of several hundreds of metres or even kilometres. The fault zones may be interconnected with other similar fault zones that can be either steeply-dipping or low-dipping. These zones are commonly much more permeable to groundwater than the remainder of the rockmass, although significant spatial variations in permeability can occur within them. The permeability variations can cause channel-like patterns of high and low permeability to exist within the fracture zones. Some complex regional faults that are tens of kilometres in length may also be tens to hundreds of metres thick.

Studies of the various geologic research areas on the Shield have also shown that near the ground surface (depths up to about 200 m to 500 m), the rock is also likely to contain networks of individual fractures or joints that are permeable to groundwater. The frequency of these permeable fractures generally decreases with depth. At greater depths (below 200 m to 500 m) the rock contains very few permeable fractures aside from the large fracture zones.

Quantitative assessments of postclosure disposal system performance and environmental impact (Goodwin et al. 1994) would commence early in the siting process, when sufficient regional scale geologic information is available from the site evaluation studies of the candidate areas to construct defensible models of the groundwater flow conditions. These initial assessments would assist in evaluating the performance of various potentially suitable vault location alternatives within the areas, help in selecting the preferred location for the disposal vault within the regional and local groundwater conditions of the candidate area and help to guide subsequent site evaluation activities at the preferred candidate sites. This approach will ensure that a disposal site is located such that any release of vault contaminants will be into long, slow groundwater flow paths. When this is combined with a disposal vault design and waste emplacement strategy that accounts for local, site specific conditions it will be possible to ensure that the disposal vault will have no unacceptable long-term impact on humans or the surrounding environment. The report by Davison et al. (1994) describes how the characterization information for the candidate area and vault site is used to develop models of the groundwater pathways from the disposal vault location to discharge locations in the biosphere.

Most aspects of the site evaluation approach that would be used for selecting and characterizing an actual nuclear fuel waste disposal site on the Shield can be illustrated by examples of the studies performed at the geologic research areas. These examples demonstrate that the technology currently exists for evaluating the technical conditions of candidate areas and sites on the Shield for nuclear fuel waste disposal.

The size scale of the geoscience investigations done at the Whiteshell Research Area is similar to that required for an evaluation of a candidate area for siting an actual disposal vault. In addition, the work done at the site of the Underground Research Laboratory (URL) at the Whiteshell Research Area has provided the opportunity to develop, test and evaluate most of the surface and underground characterization methods that would be used at an actual disposal vault site. The URL also serves as a case study of how the geotechnical information from evaluation of the candidate disposal site would be used to design, construct and monitor an actual nuclear fuel waste disposal vault.

1. THE ROLE OF SITING IN THE NUCLEAR FUEL WASTE DISPOSAL CONCEPT

The fundamental objective of a waste management system is to protect humans and the environment from any unacceptable adverse effects from the waste. Unacceptable effects are generally defined by federal and provincial regulatory agencies in terms of regulatory limits (regulatory criteria) or guidelines, either a limitation of dose to individuals in the case of radiation or a limitation of the concentration of a contaminant in the environment in the case of other toxic materials. The quantitative regulatory criteria established by the AECB for long-term protection of the environment and human health from the effects of nuclear fuel waste disposal in Canada are that:

- "there are no predicted future impacts on the environment that would not be currently accepted" (AECB 1987a, p.4)
- "the predicted radiological risk to individuals...shall not exceed 10^{-6} fatal cancers and serious genetic effects in a year" (AECB 1987a, p.5)
- "the period for demonstrating compliance with the individual risk requirements using predictive mathematical models need not exceed 10,000 years...[and] there must be reasoned arguments that beyond the 10,000 years the rate of radionuclide release to the environment will not suddenly and dramatically increase..." (AECB, 1987a, p.8).

In 1978, the governments of Canada and Ontario established the Canadian Nuclear Fuel Waste Management Program (CNFWMP) "...to assure the safe and permanent disposal" of nuclear fuel waste. AECL was made responsible for research and development on "...disposal in a deep underground repository in intrusive igneous rock" (Joint Statement 1978).

In the disposal concept that AECL has developed the Canadian nuclear fuel waste is to be buried in an underground vault. The vault would be constructed at a depth of between 500 m and 1000 m in a carefully selected candidate vault site (nominally about 5 km^2) in a candidate area (of at least 400 km^2). The vault would be located within a plutonic rock formation of a stable portion of the Canadian Shield. The Canadian Shield is the exposed portion of the ancient Precambrian rocks of North America which occurs in Manitoba, the Northwest Territories, Ontario, Québec, and Saskatchewan (Figure 1.1). Except for the Shield, the Precambrian rocks are generally covered by layers of younger rocks that are up to many kilometres thick in some places.

The disposal concept uses a system of multiple barriers, engineered as well as natural, to protect humans and the environment from the harmful effects of the nuclear fuel waste. These barriers include the waste form itself, long lived containers to enclose the waste form, a buffer material around the containers, backfill and seals within the vault, and the surrounding rock mass and groundwater regime within which the vault is constructed (Figure 1.2). Careful evaluations would be performed at

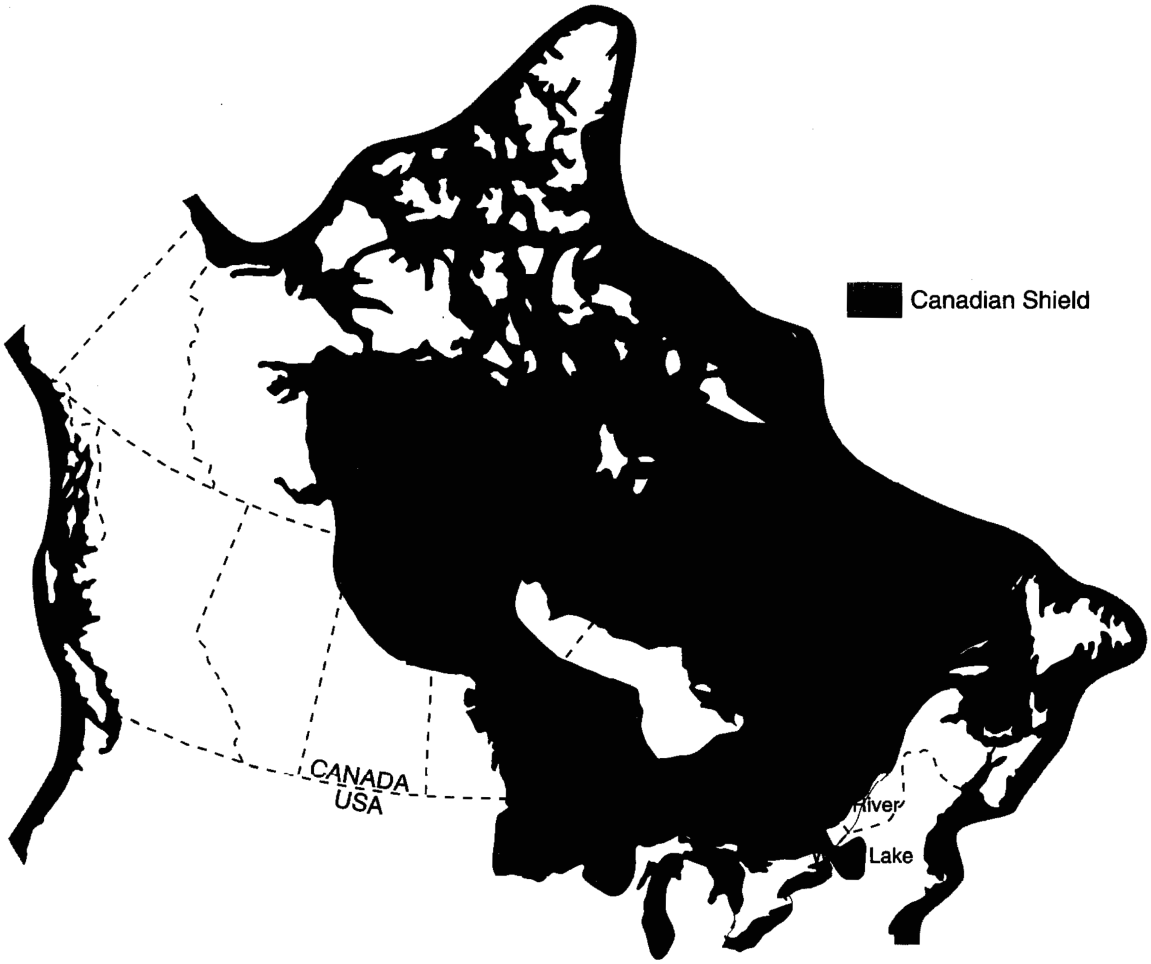


FIGURE 1-1: The Canadian Shield

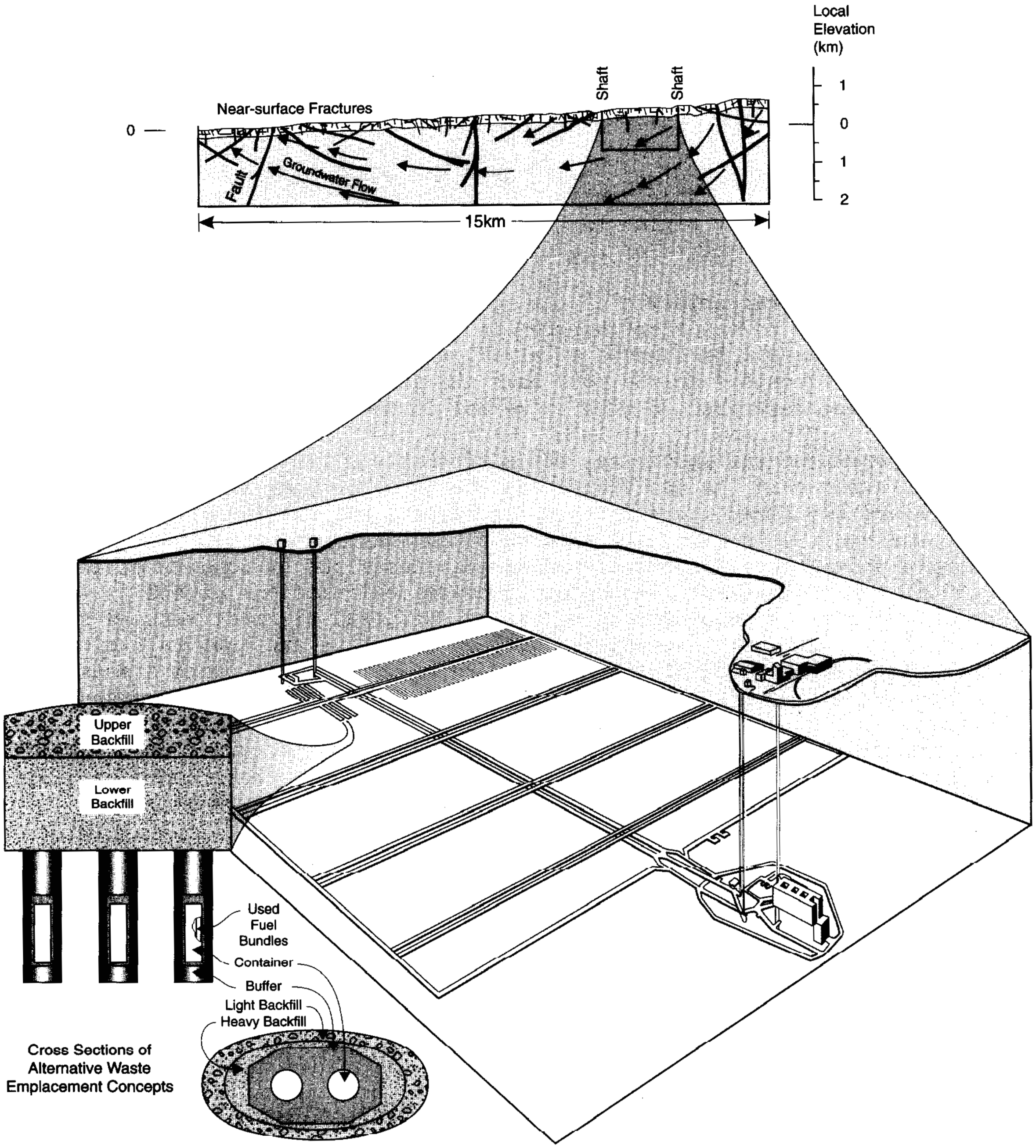


FIGURE 1-2: AECL's Nuclear Fuel Waste Disposal Concept

potentially-suitable candidate areas and sites to ensure a site is selected for the vault which will:

- inhibit future human or natural intrusions into the vault,
- delay and impede the movement of vault contaminants through the rock to the surface environment,
- allow the vault to be designed and engineered to delay the release of contaminants into the surrounding rock and groundwater regime taking account of particular features or characteristics of the site.

The chemical characteristics of the relatively insoluble waste form, which serves as an important barrier in the disposal concept, are discussed in detail by Johnson et al. (1994b). The processes governing contaminant transport in the rock mass and groundwater regime surrounding the vault are described in greater detail in Davison et al. (1994).

The disposal concept emphasizes the performance of the overall disposal system rather than its individual components. The long-term safety, health and environmental effects of locating a nuclear fuel waste disposal vault at a candidate site in a candidate area would be evaluated using a postclosure assessment methodology described by Goodwin et al. (1994). The assessment methodology provides calculations of the potential risk of combinations of various disposal alternatives and site conditions that would be compared with quantitative and qualitative risk criteria such as those of the AECB (1987a,b). The postclosure assessment methodology of Goodwin et al. (1994) would also be used to determine the sensitivity of long-term safety effects to variations in site characteristics, vault design parameters, and other factors. Additional information about the biosphere, geosphere, and vault model components of AECL's postclosure assessment methodology is given in Davis et al. (1993), Davison et al. (1994), and Johnson et al. (1994a).

1.1 OBJECTIVES AND SCOPE OF SITING

The overall objective of siting is to identify, characterize, and select a location for a candidate site that is acceptable for the disposal of Canada's nuclear fuel wastes.

No specific criteria have been developed for locating a nuclear fuel waste disposal site in Canada, however the AECB (1987b) has established the following qualitative guidelines that pertain to geotechnical conditions for a disposal vault site.

- "The host rock and geologic system should have properties such that their combined effect significantly retards the movement or release of radioactive material."

- "There should be little likelihood that the host rock will be exploited as a natural resource."
- "The repository site should be located in a region that is geologically stable and likely to remain stable."
- "Both the host rock and geologic system should be capable of withstanding stresses without significant structural deformation, fracturing, and breach of the natural barriers."
- "The dimensions of the host rock should be such that the vault can be deep underground and well removed from geological discontinuities."

This report deals almost entirely with the geotechnical aspects of evaluating and selecting a suitable candidate disposal site for Canada's nuclear fuel wastes. Some aspects of the surface environment important to siting are also presented in this report. The companion reports by Grondin et al. (1994), and Greber et al. (1994) discuss many of the socio-economic considerations that will be part of the siting process. The Environmental Impact Assessment by AECL (1994a) outlines the entire siting process and discusses how the geotechnical considerations and socio-economic considerations would be combined.

Appropriate siting of the disposal vault is important to ensuring that there will be no unacceptable impact on humans or the natural environment should any vault contaminants reach the biosphere. It is our judgment that site characterization should aim to develop a good understanding of both the regional and local groundwater flow and chemistry conditions of candidate areas and candidate disposal sites. This knowledge would be used to situate the vault in the rock and design a disposal system so as to allow the flow and chemical characteristics of the groundwater to enhance the safety of the disposal system. In addition, it is our judgement that the geologic conditions of the preferred location selected for the disposal vault should be thoroughly characterized using airborne, surface-based, borehole and underground methods. This would provide the information needed to develop an engineering design for the vault and a waste emplacement plan, that accounts for existing site specific conditions and any future changes in these conditions that might be anticipated. The methodologies outlined in this report are designed to provide such information on the conditions of the rock at potential candidate siting areas and candidate disposal vault sites.

The overall site characterization approach described in this report is a phased approach. It focuses on characterizing progressively smaller geographic areas, as siting proceeds to the selection of a suitable candidate site for locating the disposal vault and waste emplacement areas. Siting is divided into two consecutive stages, site screening and site evaluation. Site screening would use reconnaissance-type information gathering over large siting regions to identify a small number of candidate areas where potentially suitable sites are likely to exist and which warrant further investigation. Site evaluation would use

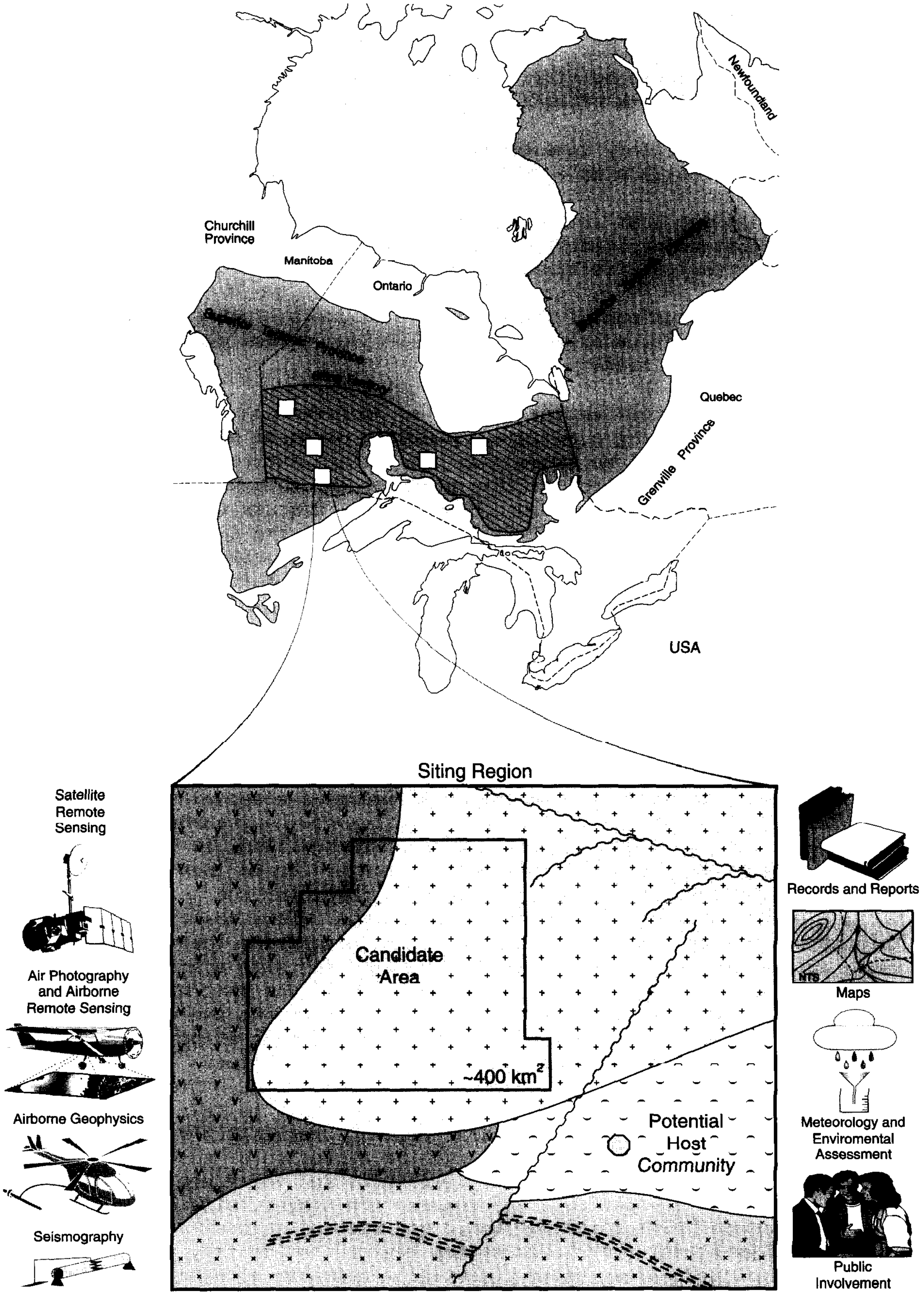


FIGURE 1-3a: Schematic of Site Screening and Site Evaluation Process

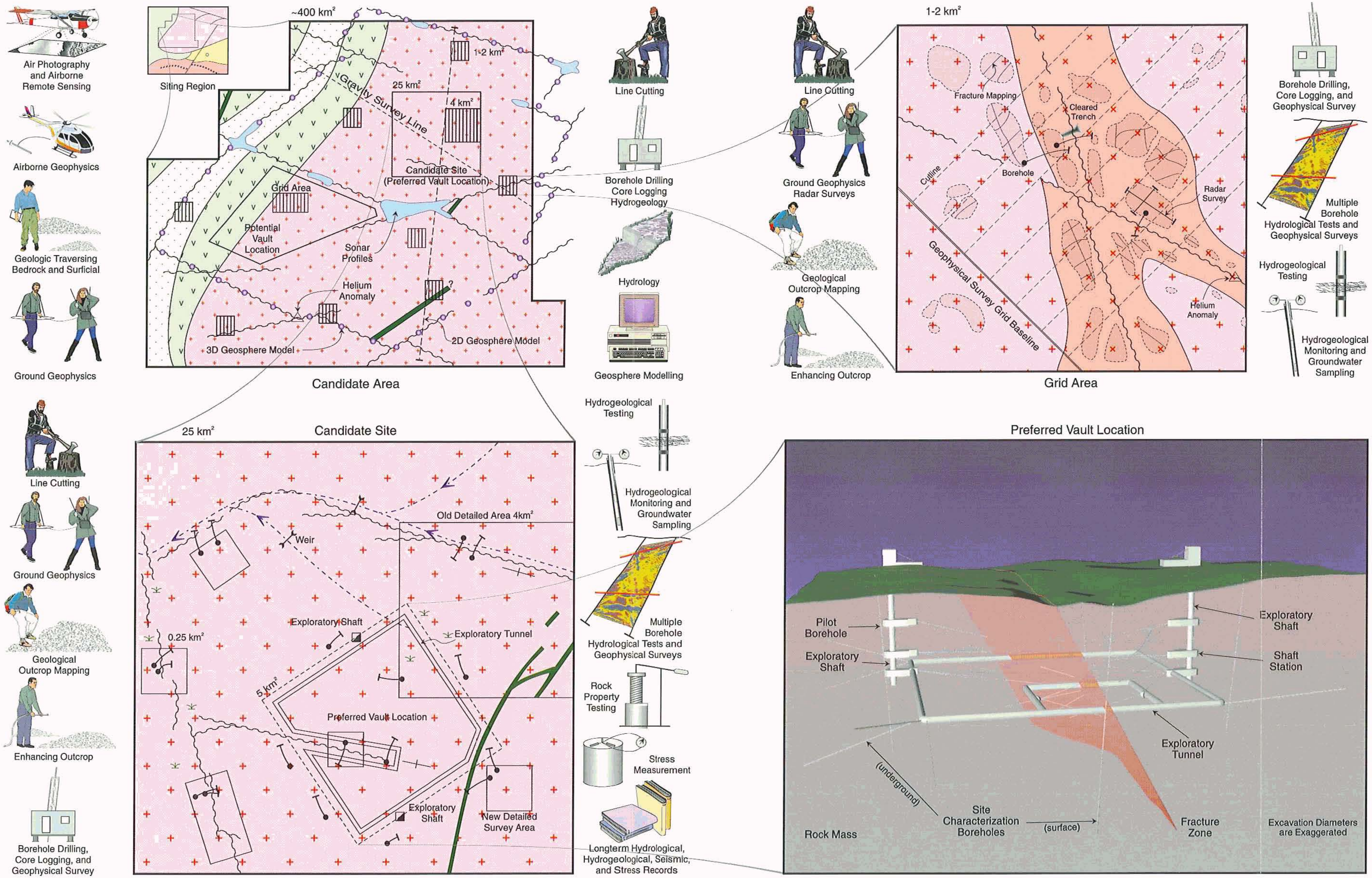


FIGURE 1-3b: Schematic of Site Screening and Site Evaluation Process

progressively more detailed airborne, surface and borehole investigations of the candidate areas to identify and assess potential vault locations and then to identify a preferred candidate site for a disposal vault. Additional information needed to select the preferred location for a disposal vault and to design the waste emplacement areas would be provided during the latter part of site evaluation. This would be done by locating and constructing exploratory shafts and tunnels at the preferred candidate site and by performing characterization activities in these underground excavations. Site evaluation would continue underground throughout exploratory construction until construction for disposal operations began at the site.

Site evaluation would provide the information needed to:

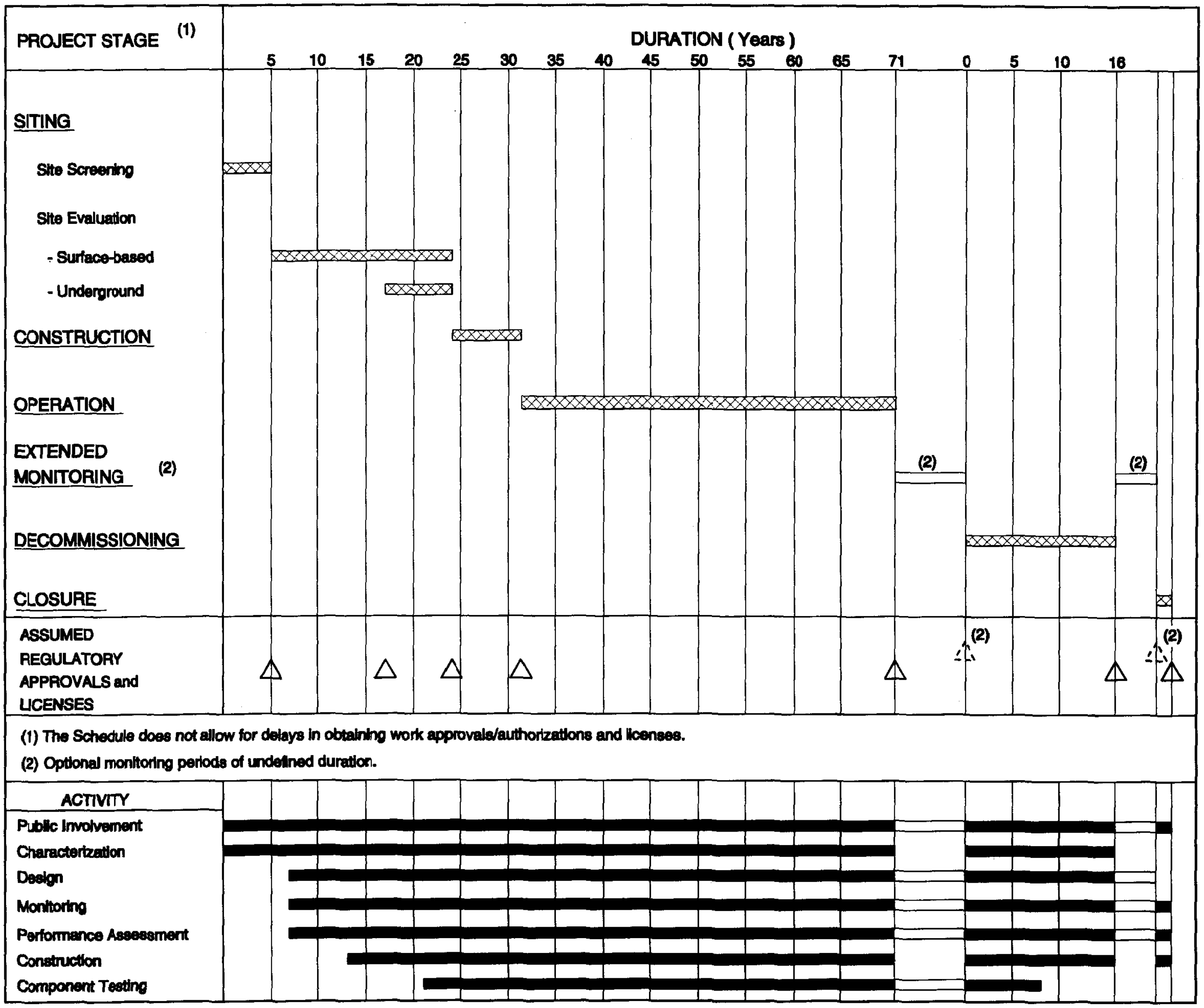
- evaluate the long-term safety, performance and environmental impact of a disposal vault at alternative sites that are potentially suitable in the candidate areas,
- prepare an application and an environmental impact statement for constructing a vault at the preferred candidate site, and
- prepare detailed designs of the surface facilities and underground vault at the preferred site.

Figure 1.3 schematically illustrates the relative size of the successively smaller areas that would be evaluated and characterized during the progressive steps of site screening and site evaluation which constitute the siting stage of the disposal project.

Quantitative analyses of postclosure performance would commence early in the siting process, when sufficient regional scale geological and hydrogeological information is available from the site evaluation studies to construct defensible models of the subsurface conditions. These initial analyses would:

- assist in evaluating various site location alternatives,
- help in selecting a suitable vault location within the regional and local hydrogeological setting,
- help develop vault designs for site specific conditions, and
- help to guide subsequent site characterization activities.

A strength of the performance assessment method that we have adopted for the disposal concept (Goodwin et al., 1994), is that it allows a mechanism by which alternative site locations and disposal vault designs can be evaluated. This allows selection of the disposal site location and disposal vault design for site specific conditions, to help ensure that the long term safety and environmental impact objectives can be achieved.



(1) The Schedule does not allow for delays in obtaining work approvals/authorizations and licenses.

(2) Optional monitoring periods of undefined duration.

FIGURE 1-4 Possible Schedule for Concept Implementation

The siting process effectively ends when construction of the disposal vault commences. However, many of the activities that were begun during the period of site evaluation would continue in the form of a continuous characterization and monitoring program throughout the remainder of the project. Such information would be needed for design and regulatory decisions during the construction and operation stages. Figure 1.4, (Simmons and Baumgartner 1994), illustrates a possible schedule for implementing the various stages and activities in the Canadian nuclear fuel disposal concept. Excavation and development of access tunnels and disposal rooms within the vault would occur over a period of at least forty years, beginning with the construction of the operating shafts and access tunnels and ending with the construction of the final waste emplacement rooms. The characterization activities carried out during this period would be an integral part of the facility design and construction process.

Monitoring of geotechnical and environmental conditions would commence at potentially suitable disposal vault locations at candidate areas during the siting stage. This monitoring would continue at the selected disposal site locations throughout the operation of the vault and be maintained for some time after the vault was backfilled and the shafts had been sealed. Thus it is expected that geotechnical and environmental conditions would be monitored at the selected disposal site for at least seventy years.

1.2 QUALITY ASSURANCE DURING SITING

Siting is the first stage of the disposal project; the construction, operation, decommissioning, and closure stages would follow. All stages of the project would be conducted under the overall guidelines of a quality assurance (QA) program (Simmons and Baumgartner 1994). The objectives of the quality assurance program during siting would be to ensure that all site screening and site evaluation activities achieve the prescribed quality, provide complete documentation and traceability of records, and provide confidence that the data can be reproduced by independent auditors if necessary. The QA program would establish and document the quality requirements for all staff, activities, instruments, software, installations, and tests used in site screening and evaluation.

Many surface and underground site characterization activities begun during site evaluation would also continue throughout the construction, operation, decommissioning and closure stages of the disposal project. These long-term activities would include the monitoring of hydrogeological, geomechanical, and environmental conditions in the surface and subsurface regions surrounding the preferred vault location. Because we would expect an observational design approach (Simmons and Baumgartner 1994) to be followed for the entire disposal project, a continuous characterization and monitoring program would be required. This would be needed to demonstrate that geotechnical conditions of the rock surrounding the vault location fall within the anticipated ranges and to demonstrate that the engineered systems are functioning properly. The information accumulated by such a characterization and monitoring program would be used upon completion of the project to justify closure of the vault and provide the evidence that the environment would be protected in the absence of institutional control. Thus it is important that all the characterization activities performed at a potential disposal site are covered by a QA program. This would ensure that data collected early in the project could be recovered and used in the later stages of the project, particularly for monitoring baseline conditions to evaluate long-term performance or environmental effects.

1.3 INTEGRATING TECHNICAL AND SOCIAL ASPECTS OF THE SITING PROCESS

The socio-economic and technical aspects of siting would need to be integrated from the beginning of the siting process to ensure its success (AECL 1994a). The approach to siting described in AECL (1994a) provides numerous opportunities for public participation throughout its implementation. Table 1.1 shows the major milestones and activities that would constitute the siting stage during implementation of the disposal concept. It also shows how technical and social aspects would be integrated into the process.

The site (and in particular the geological conditions of the rock and its groundwater flow system) is a key component of our nuclear fuel waste disposal concept and has a major influence on the safety and environmental impact of the disposal system. Geological conditions of the candidate disposal site and the surrounding candidate area will affect the preferred location, design, construction, and operation of the disposal vault. Thus the technical aspects of obtaining and understanding the geological conditions and groundwater flow conditions at the preferred disposal site and in the surrounding candidate area are very important elements of the process. This is in contrast to industrial facilities built above ground, where the suitability of the site generally can be considered independently of the specific design of the facility.

1.3.1 Site Screening Input and Consideration

It is desirable to have considerable confidence that a potentially suitable site exists in a siting region before undertaking the expense of site evaluation, vault design, and performance assessment. The screening process of siting to identify a small number of candidate areas is designed to provide that confidence. Specific criteria for screening potentially suitable candidate areas sites on the Canadian Shield will need to be established early in the siting process. It is likely that social and economic considerations will initially determine the siting regions upon which the site screening will focus. There probably will be four main sources of input to develop the screening criteria. These are:

- regulatory requirements and guidelines,
- socio-economic preferences and public consultation,
- technical recommendations of the scientists and engineers responsible for conducting the siting activities, and
- recommendations of external expert reviewers.

TABLE 1.1

THE SITING STAGE OF CONCEPT IMPLEMENTATION*

Substage	Major Milestones	Activities
Site Screening (about 3 to 5 years)	Identify any siting regions within each siting territory	- develop exclusion criteria - characterize the siting territories by analysis of pre-existing data - apply exclusion criteria
	Initiate public involvement in the siting regions	- offer information - consult regarding views and concerns about disposal and interest in participation in the siting process
	Obtain the participation of one or more potential host communities within one or more siting regions	- seek participation of potential host communities - develop framework for interaction with each potential host community - develop exclusion criteria based on the concerns of each potential host community
	Identify potential candidate areas	- continue public involvement - obtain all required approvals - characterize a region around each potential host community by analysis of pre-existing data and reconnaissance investigations - determine technical suitability - apply exclusion criteria
	Identify a small number of candidate areas	- develop and apply a ranking process if necessary

continued . . .

* For a more comprehensive discussion of the siting process, see AECL 1994a.

TABLE 1.1 (continued)

Substage	Major Milestones	Activities
Site Evaluation (about 15 to 20 years)	Identify potential vault locations within the candidate areas	- continue public involvement - obtain all required approvals - establish a procedure to seek and address the views of communities (other than the potential host communities) that could be affected by a disposal facility - characterize each candidate area and any necessary surrounding area by analysis of pre-existing data, reconnaissance investigations, studies on the surface, and studies in boreholes at grid areas - obtain baseline data and begin monitoring for changes - develop regional groundwater flow models - begin developing design options and assessing potential effects - determine technical suitability - apply exclusion criteria
	Identify a preferred vault location within each candidate area	- continue public involvement - continue monitoring - continue developing design options and assessing potential effects
	Identify candidate sites	- continue public involvement - continue monitoring - continue developing design options and assessing potential effects - define a candidate site of about 25 km² around the preferred vault location in each candidate area

continued . . .

TABLE 1.1 (continued)

Substage	Major Milestones	Activities
Site Evaluation (about 15 to 20 years) (cont'd)	Identify a preferred candidate site	- continue public involvement - obtain all required approvals - characterize candidate sites (each about 25 km^2) by detailed studies on the surface and in exploration boreholes at grid areas - continue monitoring - develop site-specific engineering conceptual designs for a disposal facility - assess environmental effects of implementing site-specific designs at specific sites - apply exclusion criteria - select measures for managing environmental effects - develop and apply a ranking process, if necessary
	▽	
	Select a transportation route and mode	- establish a procedure to seek and address the reviews of communities along potential transportation routes - obtain all required approvals - characterize relevant conditions along potential transportation routes - select a preferred route and mode for transportation of nuclear fuel waste - prepare detailed designs of the transportation system - assess environmental effects of the transportation system - select measures for managing environmental effects
	▽	

continued . . .

TABLE 1.1 (concluded)

Substage	Major Milestones	Activities
Site Evaluation about 15 to 20 years) (cont'd)	Confirm the suitability of the preferred candidate site	- continue public involvement - obtain all required approvals - characterize the preferred vault location (about 5 km^2) on the preferred candidate site by investigations from surface and in boreholes drilled from surface, detailed studies in exploratory shafts and tunnels and in boreholes drilled from them - continue monitoring - prepare detailed designs of the disposal facility - assess environmental effects of the disposal facility - review measures for managing environmental effects - continue public involvement
	↓ Obtain approval for construction of a disposal facility at the preferred site	

Because many aspects of site screening will be non-technical in nature, the actual process of developing exclusion and ranking criteria to identify a small number of candidate areas will require substantial public, government and regulatory input and participation. Throughout site screening there are likely to be one or more environmental reviews with subsequent decisions by the various stakeholders, e.g., on the acceptability of the small number of candidate areas recommended for subsequent detailed characterization during site evaluation. We have assumed that the disposal proponent (also referred to as the implementing organization) would be committed to safety and environmental protection, voluntarism, shared decision-making, fairness and openness through the site screening and site evaluation substages of the project (AECL 1994a).

1.3.2. Site Evaluation Input and Considerations

The subsequent site evaluation activities, in addition to evaluating characteristics that relate to the long-term suitability of candidate disposal sites, must also consider characteristics that are particularly relevant to the construction and operation stages of the project. For example, site characteristics that affect the capability to construct surface facilities, to excavate and maintain underground openings, and to prevent flooding of the facilities are important factors. Proximity to dwellings, public or private water supplies, surface water bodies, groundwater supplies, and areas that are either especially sensitive environmentally or that have some significant or special cultural, aesthetic, or environmental value would be considered important, either for long-term safety or for social and environmental impact during the siting, construction or operating stages of the project. Potentially-affected public groups may consider additional local factors to be significant, and these concerns would need to be incorporated by ongoing public consultation and involvement in the siting process.

During the siting process, it is possible that a candidate area chosen for detailed characterization after screening might be technically unsuitable when additional surface or subsurface information is obtained during site evaluation. This risk can be minimized by adopting an approach to siting that allows the suitability of a site to be assessed and judged continually during the siting process. Throughout site evaluation, there are likely to be a series of environmental hearings, coinciding with key milestones when decisions are required about the acceptability of the candidate areas, preferred vault locations, and preferred candidate disposal site, before the project can advance to the next step. For instance, these decisions would probably be required prior to commencing the characterization of the preferred candidate site and then prior to commencing the construction and characterization of exploratory shafts and tunnels at the preferred candidate site. Information from site characterization activities performed throughout the site evaluation substage of the project would be continuously added to previous site characterization information and used to confirm the technical suitability of the preferred candidate site for locating the disposal vault.

1.4 SCOPE OF REPORT

The remainder of this report describes the geoscience methodology AECL has developed for technical site screening and site evaluation.[1] This is based on experience acquired since 1975, when AECL began field studies at several geologic research areas on the Canadian Shield (Figure 1.1). These studies were mainly designed to develop and test methods to determine the geologic, hydrogeologic, geochemical, and geomechanical characteristics of plutonic rock sites on the Shield. Methods for characterizing environmental aspects of the surface at candidate areas and sites have also been developed and these are described briefly in this report, although the report by Davis et al. (1993) provides additional discussion of these topics.

The structure of the report follows the approach we expect would be followed for site screening and site evaluation. The report concentrates first on methods used during site screening to characterize the very large geographic areas of the siting regions and potential siting areas to identify a small number of candidate areas. The report then progresses to describe the more detailed methods used during site evaluation to characterize the candidate areas to identify a preferred vault location and a preferred candidate site. The report concludes with a description of the underground characterization that would be performed in exploratory shafts and tunnels at the preferred candidate site to confirm its suitability.

Chapter 2 provides background information about plutonic rocks of the Canadian Shield and discusses the historical development of AECL's field investigations at the various geologic research areas on the Shield. Chapter 3 discusses the technical considerations for site screening and describes the main methods used to collect geotechnical and surface environment information for site screening on the large geographic scale of siting regions. Chapter 4 discusses the technical considerations for site evaluation and outlines the overall methodology for site evaluation. Chapter 5 outlines the initial large-scale site evaluation methods that would be used to characterize candidate areas. Chapter 6 describes a method for more detailed site evaluation of the candidate areas (about 400 km^2 in size) that uses a patchwork of smaller grid areas (each about 1 to 2 km^2 in size) in which thorough investigations are conducted at surface and in deep boreholes. These studies are used to identify a preferred vault location within the candidate area. Chapter 7 describes methods for evaluating characteristics at the smaller geographic scale of the candidate site for a disposal vault location (about 25 km^2 in size). Chapter 8 describes the methods for underground characterization in exploratory shafts and tunnels at the potential vault location (about 5 km^2 in size). Chapter 9 summarizes all the site screening and site

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[1] Over the years, a number of organizations have contributed to this work including Energy Mines and Resources Canada, Environment Canada, universities and companies in the private sector.

evaluation methods described in this report. The methods are illustrated by examples from studies done at the various geologic research areas on the Shield and from studies done at the site of AECL's Underground Research Laboratory. Figure 1.1 shows the locations on the Shield of AECL's geologic research areas and the Underground Research Laboratory.

2. BACKGROUND

2.1 THE FOCUS ON PLUTONIC ROCK OF THE CANADIAN SHIELD

Virtually every country producing nuclear fuel waste currently considers land-based geological disposal to be the primary option for long-term management of this waste (AECL 1994a). During the past two decades, extensive research and development has taken place throughout the world on land-based geological disposal.

Each country makes the decision to focus on a particular rock type or types, based on geological conditions within its borders and a variety of other relevant factors. International research on land-based geological disposal of radioactive waste has concentrated on the following five disposal media: crystalline rock (generally the equivalent of what we call plutonic rock); salt; clay (or shale); tuff; and basalt.

Each of the rock types being investigated has some potentially beneficial characteristics, as well as other characteristics that are potentially detrimental to nuclear waste disposal. We refer to the characteristics of the rock type as being potentially beneficial or potentially detrimental because the effect of any of these characteristics on the safety of a disposal system depends more on site-specific conditions and disposal facility design than it does on the medium itself.

We do not believe it is possible to determine in a generic sense that any one of the various major geological media that have been proposed for nuclear fuel waste disposal is "best" technically. The location and design of a disposal facility, and any assessment of its long-term performance and environmental impact, will depend not only on generic properties of the geological medium but also on many other site specific features which are not related to the geologic medium. These include features of the surface environment such as topography, surface water drainage, biotic communities, soils and vegetation, and features of the subsurface environment such as fracturing, the groundwater flow conditions, the rock stress conditions, and the chemical conditions of the groundwater and the minerals coating the fracture surfaces.

In 1972, a committee formed by AECL, Ontario Hydro, and Hydro-Québec concluded that geological formations offer the best prospect for disposal of Canada's nuclear fuel waste (Morgan 1977). In 1974, through consultation between the Department of Energy, Mines and Resources (now Natural Resources, Canada) and AECL, it was decided to direct most of the research toward disposal in plutonic rock prevalent within the extensive area of the Canadian Shield in Ontario (Scott 1979). The decision was based on studies carried out by three branches of Energy, Mines and Resources: the Geological Survey of Canada, the Earth Physics Branch, and the Canada Centre for Mineral and Energy Technology. Subsequently, a study group chaired by Dr. F.K. Hare (Aikin et al. 1977) recommended that resources not be spread too thinly, that the primary effort be focused on crystalline rock of plutonic origin, and that careful attention be paid to the work of scientists in other countries on different rock types. The preference for plutonic rock was also supported by Ontario's Royal Commission on Electric Power Planning (RCEPP 1978). The wide distribution of plutonic rock in Ontario was an important consideration in the initial decision to concentrate the research on nuclear fuel waste disposal on plutonic rock of the Shield because Ontario is the principal region in Canada using nuclear power (Scott 1979).

AECL has concluded, following 14 years of research and development, that within the context of Canadian requirements, plutonic rock of the Canadian Shield should remain the preferred geologic medium for nuclear fuel waste disposal in Canada. AECL (1994a) provides a more detailed discussion of the rationale that led to this conclusion. Plutonic rock has many characteristics considered potentially beneficial for a disposal medium, which are discussed in the next section.

2.2 PLUTONIC ROCK

The term 'plutonic rock' broadly includes all rock that formed by solidification from a molten state, or by chemical alteration, deep within the earth's crust (at least 1 km depth). It is also often referred to as crystalline rock or intrusive igneous rock. Large individual bodies of such rock are referred to as plutons. Because they are derived from large volumes of molten rock, plutons usually have more uniform chemical properties than do the rocks into which they intruded. Plutons are classified according to the minerals that make up the rock. The light coloured granites have the highest quartz and potassium feldspar content. In contrast, the dark coloured gabbros have the lowest quartz, the highest calcic feldspar and the highest iron- and magnesium-rich mineral contents.

Although plutons were formed at considerable depth, many are now exposed because of uplift and the erosion of the overlying rocks during hundreds of millions of years. Some plutons are very large bodies, covering hundreds of square kilometres at the surface and extending to depths of 10 to 30 km. These large plutons are often referred to as batholiths.

Plutonic rock is abundant in the Canadian Shield offering great scope for siting a nuclear fuel waste disposal vault. The initial inventory of plutonic rocks of the Ontario portion of the Shield (McCrank et al. 1981) showed that there were a large number (in excess of 1000) of individual plutons and plutonic rock complexes. Granitic plutons are by far the most common in the Ontario portion of the Shield, constituting about 75% of the total plutons (McCrank et al. 1981). Gabbros are the next most abundant (15%) and all other rock types account for only 10% of plutons.

The distribution of these plutonic rock types within the Shield of Ontario is shown on Figure 2.1.

Plutonic rock of the Canadian Shield has the following characteristics which make it a suitable choice as a disposal medium for Canada.

1. Plutonic rock is widely distributed geographically. Plutonic rock of the Shield is exposed over large portions of five of the ten Canadian provinces and of the Northwest Territories (some plutonic rock is exposed in all the provinces except Prince Edward Island). In Ontario where the majority of Canada's nuclear fuel waste is currently produced, the Shield extends over more than 600 000 km^2, and more than 1000 individual plutons have been identified. Thus there are a large number of potential disposal sites in plutonic rock and these occur over a wide range of geographical conditions. Because we expect that many plutonic rock sites on the Shield would satisfy the technical requirements for safe disposal, there would be great scope for selecting a disposal site which would also satisfy social, political and economic requirements.

2. Plutonic rock occurs in a geologically stable region that is likely to remain stable. Compared with other geologic settings, much of the Shield occupies the most stable tectonic region of Canada. The entire Shield has been free of any major orogenic activity for at least the past 600 million years and the older unrifted central portions of the Shield have been free of orogenic activity for nearly 2 billion years. Seismic monitoring reveals large unrifted portions of the Superior Province of the Shield that have very low seismicity. We have concluded that locating a disposal vault in plutonic rock on the Shield, away from clustering of current earthquake activity and away from active faults, would provide adequate long term protection from the effects of earthquakes.

3. Plutonic rock is widely distributed in regions of low topographic relief. On scales greater than a few tens of kilometres, regional topographic gradients in the Shield are low, in the order of 10^{-3} (1 m per km). Because the current topographic relief is the main natural driving force for active groundwater movement through the fractures in the rock, plutonic rock located in areas of low regional topographic relief is likely to cause a low rate of regional groundwater movement in the rock.

4. Plutonic rock bodies are large. Many bodies of plutonic rock in the Shield extend over hundreds of square kilometres at surface and to a depth of several kilometres.

5. Most plutonic rock bodies are unlikely to be exploited as a resource. Many of the plutons in the Shield are not associated with deposits of currently economic minerals. Because of this,

very little mineral exploration is expected to occur in plutonic rock formations in the future. Therefore, the possibility of future accidental human intrusion into a vault 500 to 1000 m deep in plutonic rock, by activities such as exploratory drilling for economic minerals, is remote and certainly much less than for most other rock types.

6. Plutonic rock has potentially beneficial thermal properties. The thermal properties of plutonic rock would allow heat from nuclear fuel waste to dissipate readily. Granitic rock conducts heat somewhat better than gabbroic rock, but engineering studies have shown that either of these plutonic rock types can readily satisfy thermal constraints that are expected for vault designs.

7. Plutonic rock on the Shield has potentially beneficial hydrogeological properties. Transport by diffusion or advection in groundwater, within the fractures and pore spaces in the rock, is the most significant mechanism by which radionuclides could be brought to the surface from a deep disposal vault. Field investigations at research areas on plutonic rocks of the Shield have shown that at the depths proposed for constructing a disposal vault (500 m to 1000 m) there can be large volumes or blocks of sparsely fractured, very low permeability plutonic rock. These are bounded by major zones of fracturing but are free of such features within them. Locating disposal rooms in a vault within such intrablocks of very low permeability plutonic rock would serve to limit access of groundwater to the waste. This would slow the deterioration of the engineered containment and of the waste form itself, and would inhibit transport of radionuclides through the rock. In some regions of the rock the groundwater movement is so slow that transport would be controlled by ionic diffusion rather than advection. Locations can be found at depths of 500 m to 1000 m in plutonic rock formations where large volumes of the rock have very low permeability or there is a combination of low permeability and low natural hydraulic gradients. These conditions would create extremely slow groundwater movement along long transport paths through the rock, which will inhibit and delay the transport of any radionuclides leaking from the vault.

8. Plutonic rock has potentially beneficial geochemical properties. Minerals that constitute plutonic rock, and coat the pores and fracture surfaces within the rock, react with many of the radionuclides in nuclear fuel waste in such a way as to prevent or greatly retard their movement through the rock. This serves to further decrease the rate at which these radionuclides would be transported in groundwater through the pores and fractures in the rock.

9. Plutonic rock has potentially beneficial geomechanical properties. Field and laboratory investigations of rock stress and strength, together with theoretical analyses of rock creep indicate that stable underground excavations can be made at depths of 500 m to 1000 m in plutonic rock of the Canadian Shield. After these openings have been back filled and sealed during the waste emplacement operations, the rock adjacent to the excavation should experience very low deformation during the minimum design life of the waste containers (500 years, Simmons and Baumgartner 1994). Stresses in the rock will not be transmitted to waste containers in the early years of the vault. This facilitates the longevity and hence safety of containers, and enables the use of existing hard rock mining excavation technology in vault engineering and construction.

2.3 THE CANADIAN SHIELD

Many geotechnical characteristics of plutonic rock bodies of the Canadian Shield are determined by their age and style of emplacement and by subsequent deformations that have affected them and surrounding rocks. Because of this, it is important to understand the overall geological history of formation and deformation of the Shield.

The Canadian Shield is largely comprised of continental crust which formed during the Archean Eon (>2.5 billion years ago). During and shortly after its formation, some major periods of deformation occurred as a result of crustal plate movements or plate tectonics which disrupted the Shield. These deformations, which are shown schematically in Figure 2.2, involved continental break-up, crustal accretion to the continental craton (older, more stable crust) through continental collisions, and the formation of new lithosphere by intrusion and underplating (Sun 1989). These tectonic events gave rise to uplift and mountain building, sedimentary basin development, rifting, volcanism, the intrusion of plutons and metamorphism. The time periods during which these events occurred are referred to as orogenies, and the physical locations of the events with their suite of rocks and deformations, are referred to as orogens.

Deep erosion, largely in Precambrian time has exposed the roots of the orogens that were welded together to form the Shield. Within each orogen, the trends of the geologic structures and the age of the deformations are similar and they have been used by geologists to subdivide the Shield into various structural provinces. Figure 2.3 shows the currently recognized geologic structural provinces on the Shield.

The rocks of Archean age on the Shield have been divided into seven structural provinces: the Superior, Wyoming, Slave, Nain, Hearne, Rae and Burwell (Figure 2.3). The Hearne, Rae and Burwell Provinces were formerly grouped together as the Churchill Province. It is believed that these seven Archean structural provinces were originally microcontinents of the earth's early crust: each a late Archean aggregate that underwent

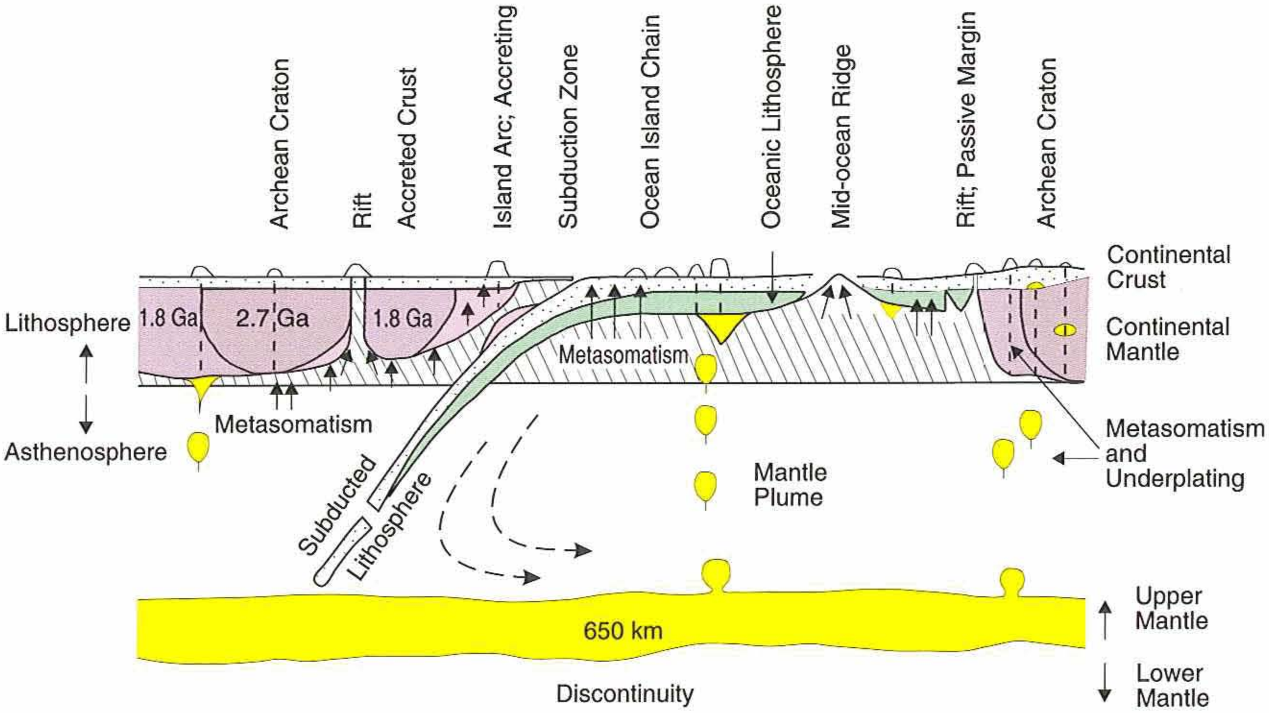


FIGURE 2-2: Schematic of Plate Tectonic Processes and Their Role in Craton Formation (adapted from Sun 1989)

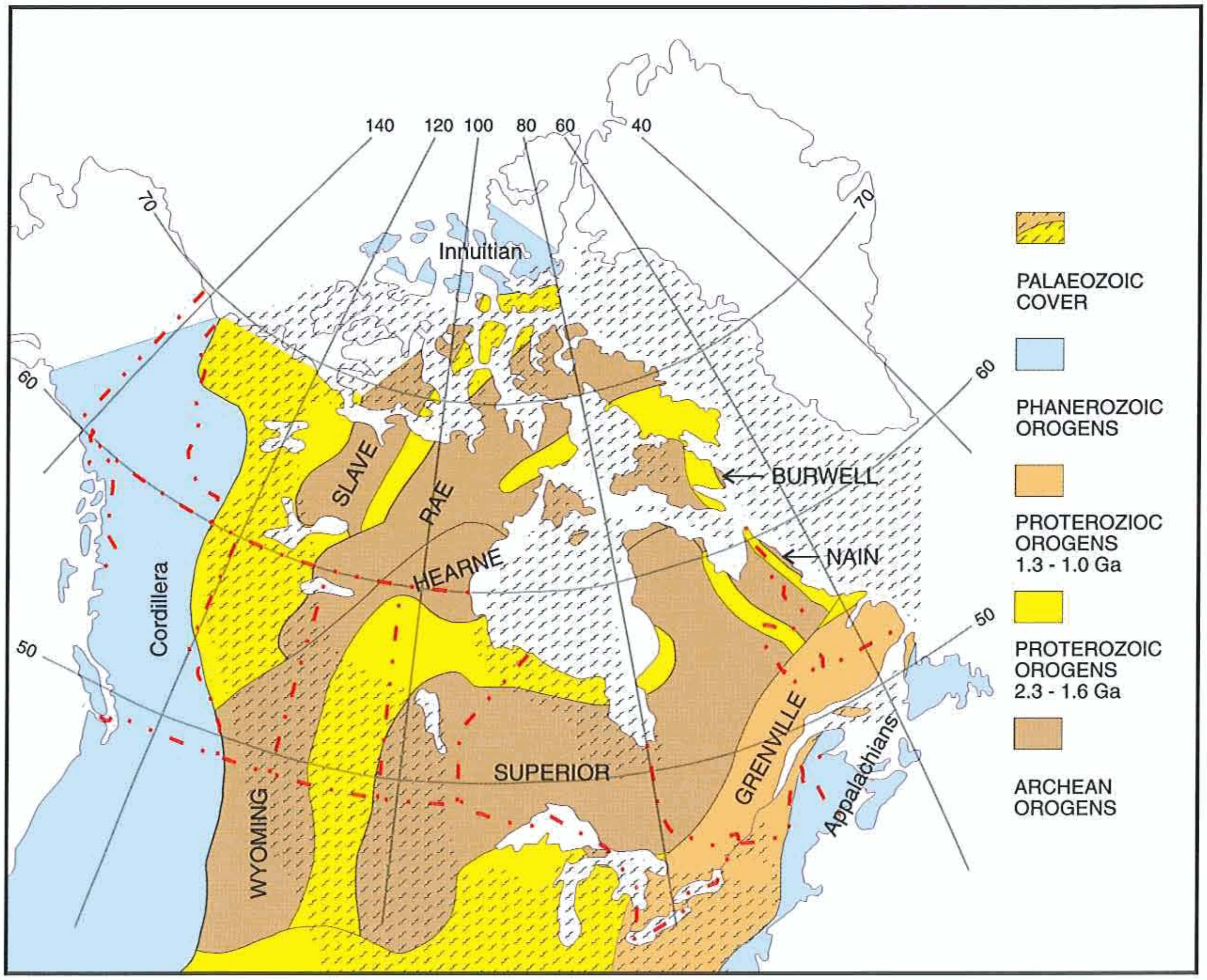
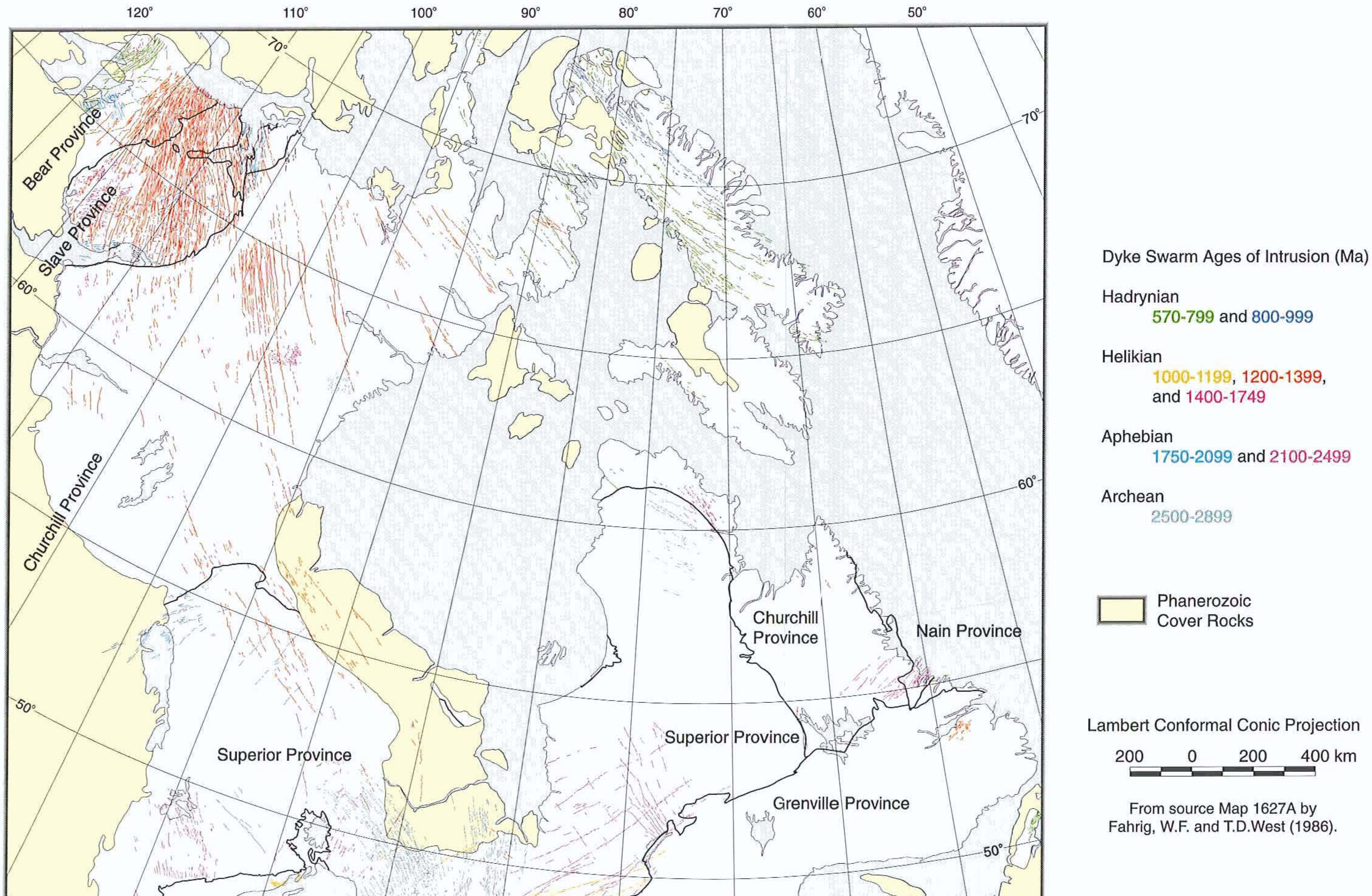


FIGURE 2-3: Geological Structural Provinces of the Canadian Shield (modified after Hoffman 1989)



From source Map 1627A by Fahrig, W.F. and T.D.West (1986).

strong compressional deformation, accompanied by pluton emplacement and metamorphism, between 2.8 and 2.6 billion years ago. The present dimensions of these structural provinces are governed by rifting and by welding caused by collisional orogens that occurred during the Early Proterozoic between 1.98 and 1.83 billion years ago. Of these internal orogens, only the Trans-Hudson orogen contains a significant width of younger Proterozoic crust (up to 400 km). The orogens flanking the Archean protocontinent contain appreciable accretionary younger crust, ranging in age from 2.4 to 1.65 billion years old. To the south, this younger crust was reworked, and further crust added, by the Grenvillian orogeny, which occurred 1.2 to 1.0 billion years ago, but the Shield was largely assembled 1.65 billion years ago (Hoffman 1989).

Several post-orogenic sedimentary basins and igneous suites within the Shield range in age from 1.8 to 1.2 billion years old. Between 1.3 and 1.1 billion years ago scattered alkaline igneous complexes, and extensive mafic dyke swarms, that fed large plateau lava flows, intruded the Shield. Figure 2.4 shows the distribution of these dyke swarms on the Superior Province of the Shield. On the western and northern margins of the Archean continent, sedimentary basins formed between 1.6 and 0.8 billion years ago.

Between 800 and 500 million years ago rifting created the continental margins of the Shield, which later evolved into the Phanerozoic orogens. Shallow Phanerozoic seas covered the Shield and blanketed the Shield rocks with marine sediments. Remnants of this sedimentary cover, and of late Proterozoic weathered, erosional surfaces can presently be found throughout the Shield.

For most of the plutons that are currently exposed in the Superior Province, considerable time elapsed between the time they were initially intruded and the time they had cooled sufficiently to undergo crystallization. During that time of cooling and uplift, the plutons were subjected to many periods of non-orogenic deformation. The tectonic deformations that have affected the Shield since its formation are discussed in Card and King (1992) and are illustrated in Figure 2.5. The time-range of the Kenoran Orogeny, which occurred during the Archean, and the time ranges of the Proterozoic, Hudsonian and Grenville Orogenies are also shown on this figure. These orogenies were followed by various local epeirogenic uplifts and subsidences in the Phanerozoic Eon.

Similar minor disturbances undoubtedly occurred during Proterozoic time, though they cannot be readily recognized in the geological record of the Shield rocks. In the simple terms of Figure 2.5, the orogenies are periods of mountain building and intrusion, major faulting, rapid erosion and sedimentary deposition. In the plutonic environment, ductile deformation also occurred. In the time between orogenies, slow sedimentation commonly occurred in basins below sea level. These less violent disturbances either created new faulting or introduced fluid circulations that affected the previous faults.

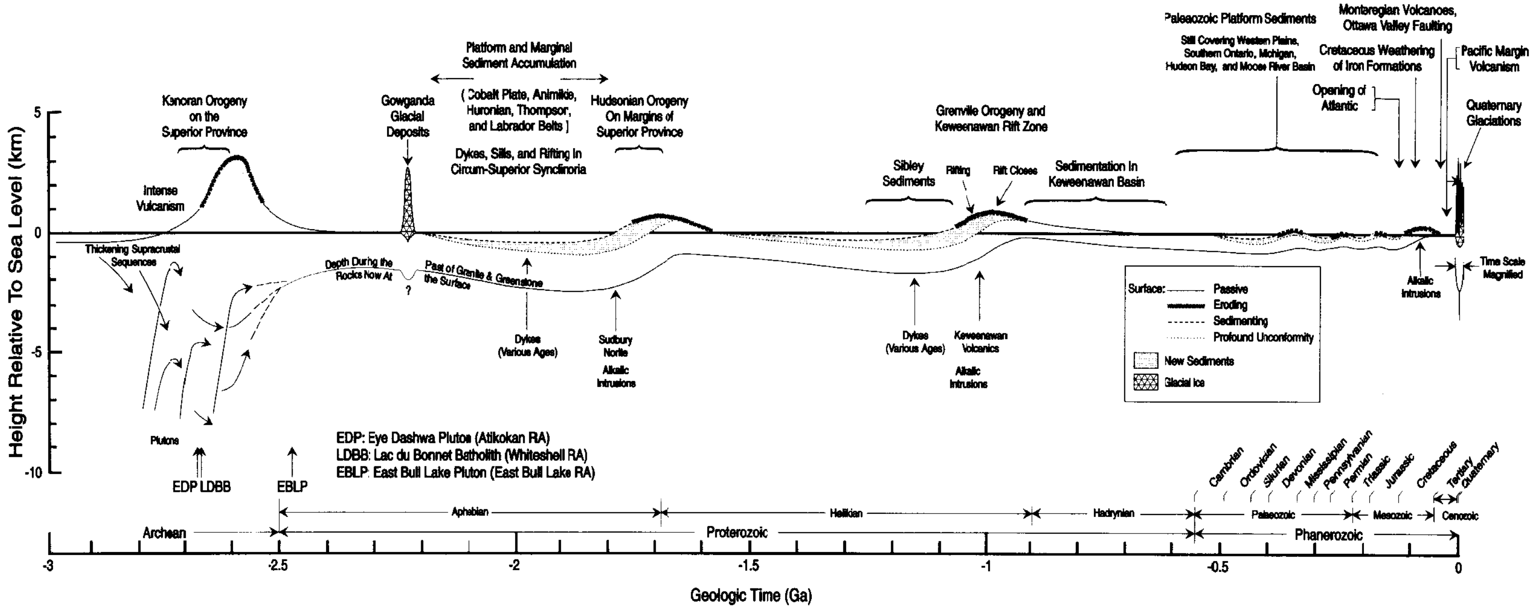


FIGURE 2-5: Tectonic Deformation that have Affected the Canadian Shield (modified from unknown source)

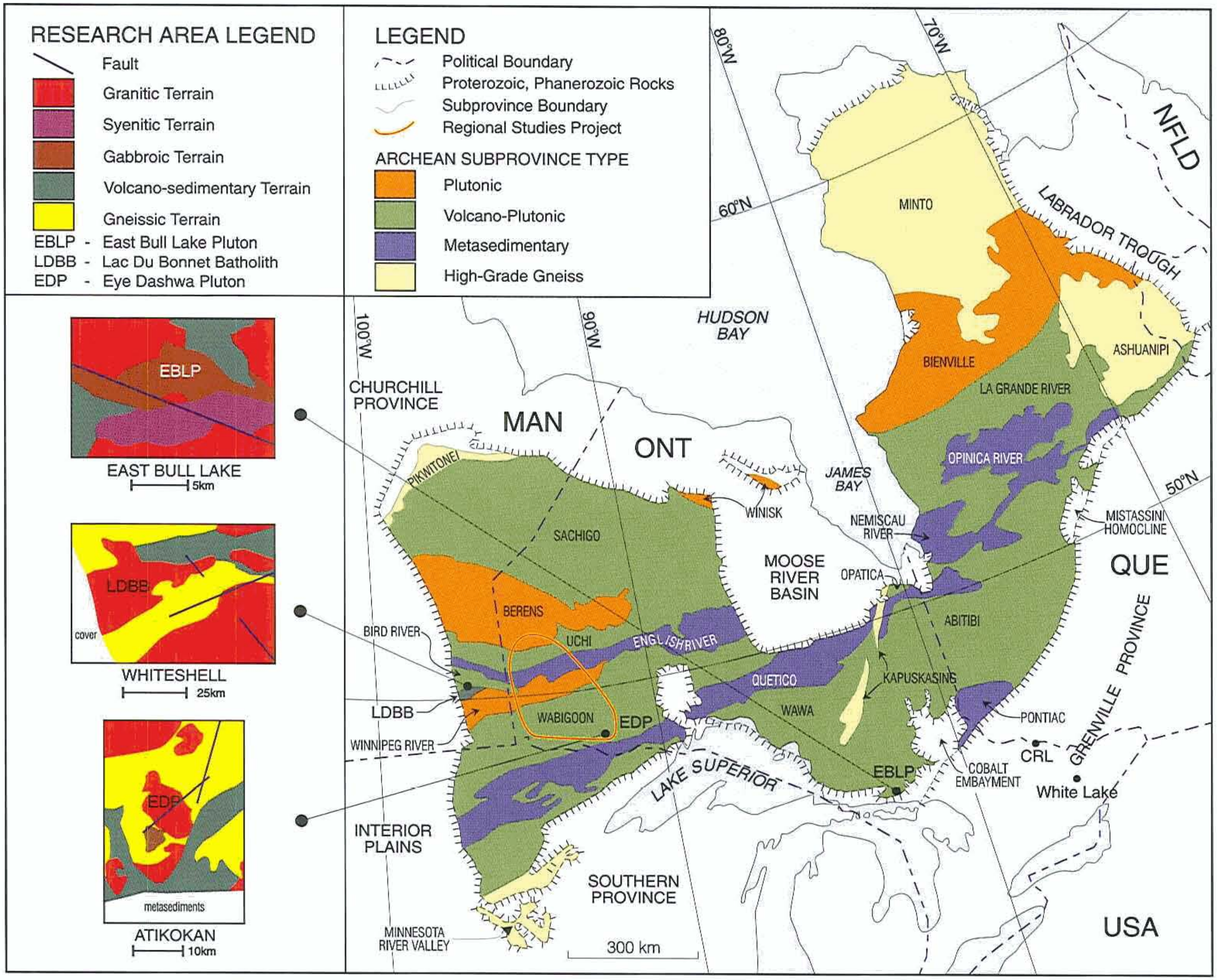


FIGURE 2-6: Location of Research Areas and Subprovinces of the Superior Province in the Canadian Shield (modified after Card 1990)

The two most recent continental glaciation events that have left observable traces on the Superior Province are also shown in Figure 2.5. In addition, several episodes of Proterozoic and Phanerozoic, non-orogenic intrusion, that have also affected the Shield, are shown. The combined effect of this long geologic history is that any plutonic rock body in the Superior Province which is now exposed at surface, has undergone several periods of tectonic brittle deformation. These periods of deformation created the faulting and fracturing that are now observed in these rocks.

In very general terms, those plutons which intruded the Shield during an orogeny should be much more deformed than those which intruded after the orogeny. However, the intensity, location and timing of the deformations that can occur during an orogeny can vary widely. Because of this, it can be very difficult to determine the precise timing of some intrusions with respect to the timing of an overall orogeny particularly if the orogeny and the intrusion occurred in the Archean. An added complication is that those plutons which crystallized near surface are characterized by less homogeneity and more brittle (as opposed to ductile) deformation than those which crystallized at deeper levels in the crust. Thus we prefer to use the terms "pre-, syn- and post-tectonic" rather than the terms "pre-, syn- and post-orogenic" to describe the likely style and degree of intensity of deformation in plutons of the Shield, particularly in the Superior Province of the Shield.

Archean rocks of the Superior Province constitute most of the Shield in Ontario and Quebec. The Superior province is the least complex of the seven Archean provinces of the Shield but it typifies the common range of Shield terrains. Successive accretion formed subparallel, east-northeast trending, compressed belts of contrasting lithology, age and/or metamorphic grade known as subprovinces (Figure 2.6). The belts, within the Superior Province are of four types:

1. Volcano-sedimentary-plutonic terrains, representing island arcs, composed of lava flows and fragmental rocks, with sediments derived from eroding volcanoes and plutons from molten rock which cooled deep in the subsurface. In these environments the metamorphism is commonly low grade and the plutons are commonly granitoid in composition.

2. Sedimentary terrains with low grade metamorphism, that probably represent accretionary prisms in sinking depositional basins at the craton margins.

3. Complexes of multiple plutonic intrusions; these probably represent blocks of earlier continents caught up in the volcanic island arcs of the volcano-sedimentary-plutonic terrains.

4. High-metamorphic-grade gneiss complexes representing deeper erosional levels of the other belt types.

Faulting and folding of the rocks are found at all levels of intensity and scale in these terrains. Other structural provinces of the Shield are similar to the Superior Province but tend to be more complex and their sequences of formation are less well known.

Three of AECL's four main field research areas are located on rocks of the Superior Province (Figure 2.6). The East Bull Lake Research Area is situated on a gabbroic pluton in central Ontario near the contact between the Superior, Grenville and Southern Provinces; Atikokan is situated on a granitic pluton in northwestern Ontario in the Wabigoon subprovince and Whiteshell is situated on a granitic pluton in eastern Manitoba in the Winnipeg River subprovince. The Lac du Bonnet Batholith and the Eye Dashwa pluton were both intruded in the Archean Eon (Figure 2.5), which ended 2.5 Ga ago. The East Bull Lake Pluton was intruded a little later, early in the Proterozoic Eon that followed the Archean. The other major research area, Chalk River, is located in eastern Ontario on gneissic rocks of the younger Grenville Province. The White Lake Research Area is located on a fine- to medium-grained biotite granite pluton in gneissic metamorphic terrain of the Grenville Province.

2.4 HISTORICAL PERSPECTIVE OF AECL'S SITE EVALUATION RESEARCH AND DEVELOPMENT PROGRAM

AECL's field research on site evaluation methods for plutonic rocks began in 1975 with investigations at the White Lake Research Area. This work was discontinued in 1976. Simultaneous investigations began at the Chalk River and Whiteshell Research Areas in 1977. Investigations at the Atikokan and East Bull Lake Research Areas were initiated in 1979 and 1981 respectively. The work at Chalk River was discontinued in 1983. Routine long term monitoring of hydrogeologic conditions has been maintained at the Atikokan and East Bull Lake Research Areas. Work is also still continuing at the Whiteshell Research Area to provide long term data on hydrogeologic, hydrogeochemical and hydrologic conditions of the Lac du Bonnet Batholith.

The early site evaluation research at White Lake, Chalk River and Whiteshell was aimed 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 larger regional size scale (500 to 1000 km^2; and up to 1.0 km in depth, Betcher and Pearson 1982). The other direction has been toward developing methods for site evaluation within underground excavations. Particular emphasis has been placed on developing methods to assess near-field conditions in the rock and to determine changes caused by the construction and operation of a disposal vault (Davison and Pearson 1982).

The near-field site characterization research has been mostly performed in the Underground Research Laboratory (URL). This facility was constructed to a depth of 450 m in a previously undisturbed portion of the large granitic Lac du Bonnet Batholith within the Whiteshell Research Area (Simmons and Soonawala 1982, Simmons 1988). Construction of the URL began in 1984 and continued until 1990. The siting, construction and operation of the URL have provided an opportunity to test and develop most of the surface and underground site characterization methods that would be used at an actual disposal site.

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 (WRA) (Davison et al. 1989). The work at the WRA has covered a 500 km^2 area of the granitic Lac du Bonnet Batholith encompassing AECL's URL and WL properties. This has involved studies at seven grid areas including the drilling, testing, sampling, and monitoring of 32 boreholes to depths exceeding 250 m, 14 of these to depths of 500 m to 1200 m.

In addition to these specific research areas AECL has conducted a large reconnaissance investigation of plutons in five different structural provinces of the Shield in northwestern Ontario. This work has been used to relate the geological conditions on these plutons to the regional geologic setting and to conditions on the plutons at the Whiteshell and Atikokan research areas. The location of this large reconnaissance study area is also shown on Figure 2.6.

It is important to recognize that these geologic research areas were selected because they offered opportunities to test and develop site evaluation methods in a variety of different lithologic and structural environments on the Canadian Shield. They were not selected because they might prove to contain suitable sites for locating a nuclear fuel waste disposal vault (Farvolden et al. 1985). Thus the approach to site evaluation at these research areas has been different in some respects from the approach that would be followed in siting a nuclear waste disposal vault. The scope of the studies and the timing and the sequence of activities that have been followed at the various research areas are quite different from those we outline in Chapter 5. Nevertheless it is our judgement that the approach for evaluating a potential disposal site can be illustrated by describing examples of the studies at these research areas. The examples demonstrate that the technology has been developed for evaluating the geotechnical conditions of plutonic rocks of the Canadian Shield for characterizing potential candidate siting areas (about 400 km^2 in size), potential candidate disposal sites (about 25 km^2 in size) and potential vault locations (about 5 km^2 in size).

3. TECHNICAL FACTORS IN SITE SCREENING

3.1 INTRODUCTION

Site screening refers to the process used to identify a small number of potentially suitable candidate areas of plutonic rock for thorough surface and subsurface site characterization investigations, out of larger siting territories and siting regions of the Canadian Shield. Regardless of which approach is adopted in Canada to initiate siting of a nuclear fuel waste disposal vault, the site screening process should include the following components:

- development of regional site exclusion criteria,
- application of the regional site exclusion criteria to the siting territories to prepare a map of siting regions of the Shield available for consideration,
- identification of potential candidate siting areas and obtaining the participation of potential host communities within the siting areas,
- development of site exclusion and selection criteria for the potential candidate areas,
- application of the site selection criteria to the potential candidate areas remaining after exclusions to prepare a map of all potentially suitable candidate areas,
- development of ranking criteria,
- application of the ranking criteria to the potentially suitable candidate areas to prepare maps and tables of those areas categorised by rank, and
- identification of a small number of candidate areas for subsequent site evaluation studies.

Based on the siting guidelines of the AECB (1987b) and the knowledge gained through field studies of plutonic rocks of the Shield, there are a number of technical factors important in screening siting territories, siting regions and potential candidate areas of the Shield for locating a disposal vault. The following factors help to determine if potentially suitable disposal sites are likely to exist in the siting territories and regions to identify a small number of potentially-suitable candidate areas where further technical characterization appears warranted:

- rock mass stability, seismicity and seismic risk,
- mineral resource and alternative use potential,
- geological setting,
- hydrology and hydrogeologic setting,
- degree of fracturing in the rock, and
- surface environment and environmental sensitivity.

Each of these is discussed below.

3.2 ROCK MASS STABILITY, SEISMICITY AND SEISMIC RISK

The state of in situ stress in the rock controls the stability of the rock. The in situ stress is a function of gravitational attraction, forces due to active tectonism and also any remnant stress remaining in the rock mass from past geologic or tectonic events. Of these, the forces caused by active tectonism are the most important. Measurements of in situ stress and other crustal stress indicators suggest the maximum deviatoric compressional stress is oriented in a NE-SW direction over most of eastern Canada including the Canadian Shield. The orientation and magnitude of this stress field is believed to be controlled mainly by the large-scale crustal forces in the earth and the continental plate motion associated with the mid-Atlantic Oceanic spreading ridge. The old Archean-Proterozoic terrains of the continent are extremely rigid and strong (Bechtel et al. 1990, Kusznir and Karner 1985) and modelling indicates that these terrains are very unlikely to fail under present-day stress conditions (Kusznir and Park 1982, 1986). However stress concentrations do occur in the Shield as a result of lithosphere heterogeneity (such as the existence of ancient rift systems), glaciation and isostatic rebound, denudation, or localized tectonic processes (such as the passage of the North American continental plate over mantle hot spots).

Knowledge of the rock mass stability, seismicity and seismic risk of the Shield is required during site screening to determine if rock movements could occur that would affect the safety of a disposal vault either during the construction or operation phases of the vault or during the long term hazardous lifetime of the emplaced wastes. Rock movements can occur either suddenly as dislocations along new or previously existing fractures, causing elastic energy to be transmitted seismically through the rock, or gradually by the process of creep. Because sudden (seismic) rock movements create new fractures in the rock mass or change the character of existing fractures, seismicity is of primary concern in assessing the stability of the rock mass. Information about current rates and trends in seismicity is gathered directly by monitoring seismic activity. Information about past seismicity (i.e., beyond 100-200 years ago) is gathered indirectly by examining geologic evidence for the timing, orientation and magnitude of dislocations along fractures in the rock.

The Canadian National Seismic Monitoring Network began monitoring the seismic activity in eastern Canada in the 1930s and this monitoring shows that relative to the world-wide and Canada-wide seismic activity, most of the Shield is a region of the least seismicity in North America (Figure 3.1). Despite this very low seismic activity, earthquakes do occur in the Shield from time to time, and it is important to identify zones of differing seismicity within the Shield. Based on the work of Basham et al. (1985), Adams and Basham (1989, 1991) and Wetmiller and Cajka (1989), a few moderate to large earthquakes (i.e., greater than magnitude 4.0 (M 4.0) on the Richter scale) have been recorded in the exposed portion of the Shield of eastern Canada. These are associated with the Timiskaming Rift and Kapuskasing Structural Zone around Timmins, Ontario and with the Ottawa-St. Lawrence Rift System. These are regions of structural weakness due to ancient rifts in the North American plate which appear to focus the small amount of seismic activity that occurs on the Shield. They are also the only locations on the Shield where significant earthquake movements have occurred since the Proterozoic.

In order to improve the accuracy of monitoring the seismic activity of the Shield, particularly the region west of the Kapuskasing Structural Zone, AECL supported the installation of the Northern Ontario Seismograph Network in 1982. This network consists of six seismograph stations which allows the accurate detection of even very small seismic events. The network can detect seismic events caused by rock bursts or collapses in active or abandoned mines. Figure 3.2 shows the locations of the seismic events of magnitude greater than about 2.5 that have been detected by this network since its installation.

The large portion of the Shield, west of the Kapuskasing Structural Zone extending into western and northwestern Ontario and into northeastern Manitoba, has been free of any significant earthquake activity (i.e., $M > 4.0$) since seismic monitoring of this region of Canada began in the 1930s. A few very small events of magnitude 2.5 to about 3.5 have recently been recorded by the high resolution seismic monitoring network installed by AECL. Although these cannot be readily associated with particular regions of known structural weakness such as fault zones, most of these occur within the volcano-plutonic belts of the Wabigoon, Wawa and Sachigo subprovinces of the Shield.

Seismic zoning maps aid the engineering and construction industries in assessing seismic hazard in different regions of the Canada (Basham et al. 1985). The six seismic zones in Canada are based on the risk of seismic damage to surface structures that are built without using earthquake resistant designs. The seismic zone boundaries are related to the seismic ground motion values that have a 10% chance of being exceeded during a fifty year period within that zone. Seismic zone 0 represents negligible risk, zone 1 minor risk, zones 2 and 3 moderate risk and zones 4, 5 and 6 high risk. Most of the Shield of Ontario is in seismic zone 0, although portions of the Shield in eastern Ontario are in zones 1, 2 or 3 (Figure 3.3).

Because of the very low seismicity and the short historical record for earthquake occurrence on the Shield, there is considerable uncertainty in estimating the long term seismic hazard. However, the hazard is lower than it is elsewhere in Canada and a disposal vault located on the Shield, outside areas where current seismic activity is concentrated, would be in a region that is geologically stable and likely to remain stable. Atkinson and McGuire (1993) and Atkinson (1993) have done preliminary probablistic seismic hazard evaluation for the unrifted portion of the Shield in northwestern Ontario using the world-wide earthquake magnitude/frequency relationships for unrifted stable continental interiors developed by Johnston and Kanter (1990). These evaluations have indicated that so long as no seismically active fault

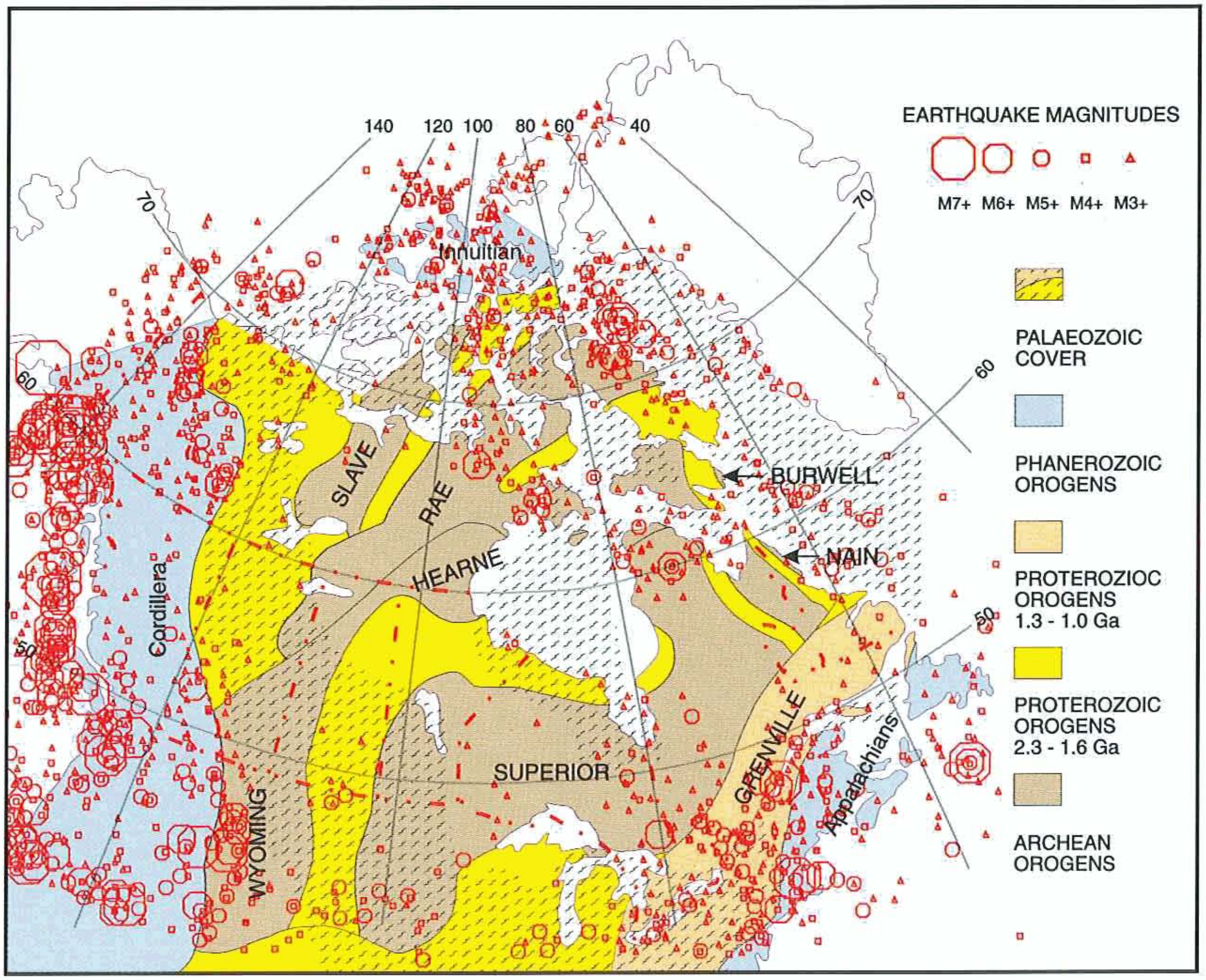


FIGURE 3-1: Seismicity of Canada

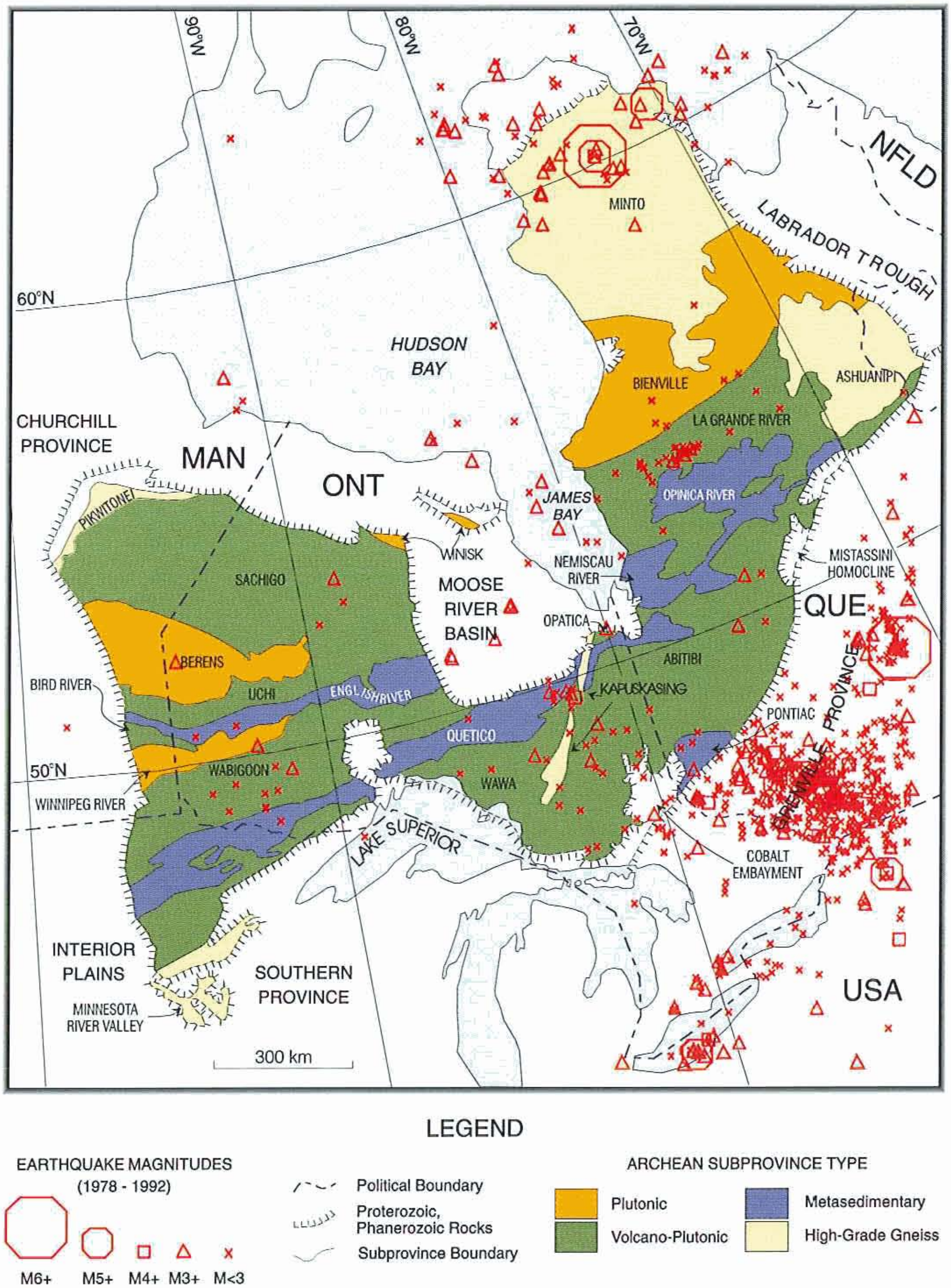


FIGURE 3-2: Seismicity of Central Canada

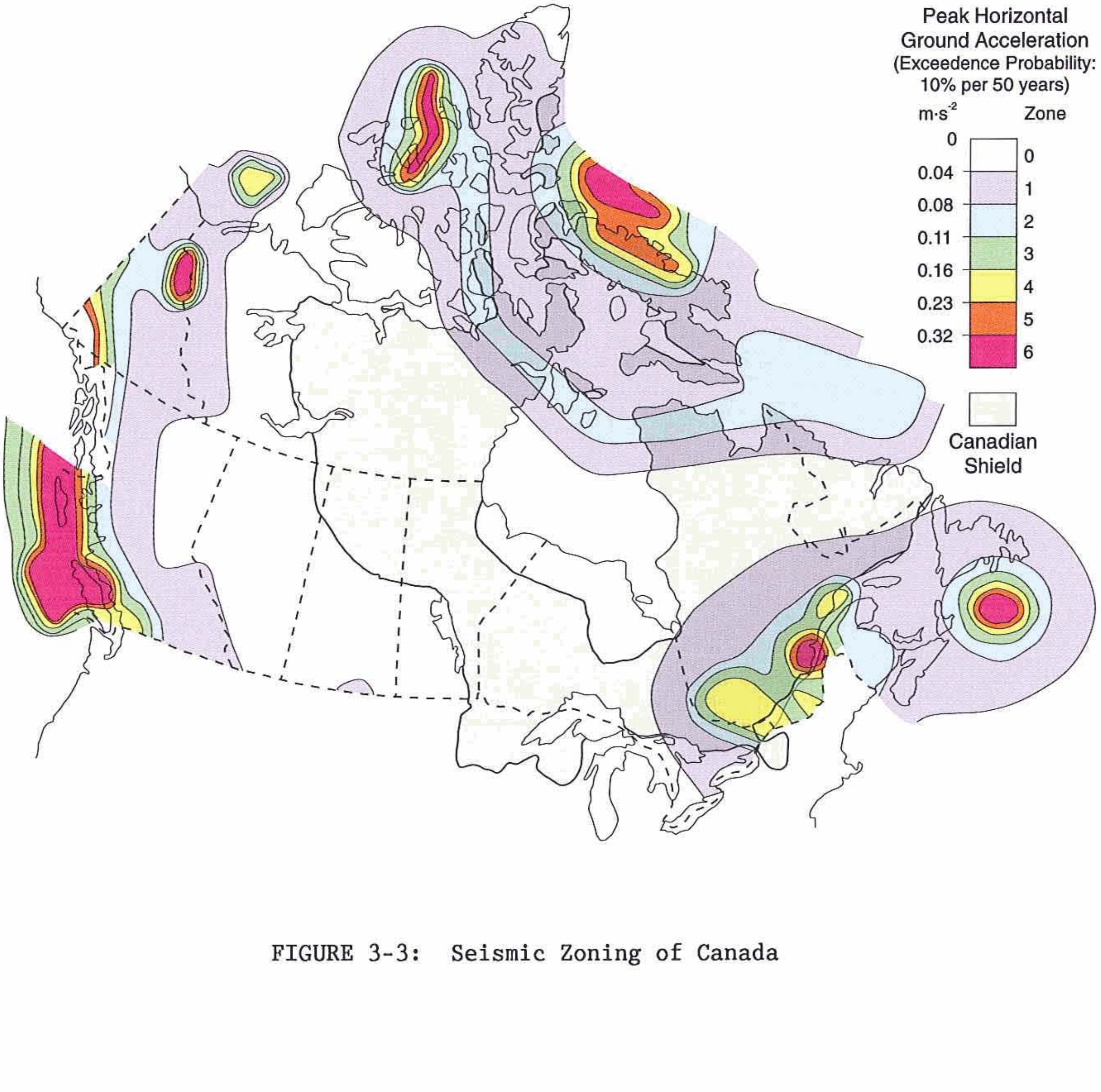


FIGURE 3-3: Seismic Zoning of Canada

was within 50 m of the disposal vault the annual probability of an earthquake capable of causing fracturing to reach the disposal rooms for a disposal vault in this region of the Shield would be less than $5 \cdot 10^{-7}$. This probability could be reduced to effectively zero by keeping the disposal vault location more than 1 km away from any active fault that was 2 km in length or 200 m away from an active fault 5 km in length (Atkinson and McGuire 1993).

There are two major aspects of seismicity that are of concern to siting a nuclear fuel waste disposal facility. One concern is that building structures on the surface would be damaged directly by an earthquake. This is of particular concern for the facilities for handling and packaging the wastes. The other concern is whether the geology or hydrogeology at the site is such that conditions could change in response to an earthquake. Damage might occur to the waste containers, buffer, backfill, or seals in the disposal vault, or faults might be created (or reactivated) in the surrounding rocks to provide new (or enhanced) groundwater flow pathways to surface. Both concerns can be addressed during screening by avoiding areas of recorded seismic activity, by avoiding areas having postglacial fault movement (Adams 1981) that appears to extend to significant depth (i.e., beyond a few tens of metres), by avoiding areas of ancient rifting, and by avoiding areas where thinner crustal plates exist such as the paths of mantle hot spots across the Shield.

As a further precaution, we could adopt standards developed for CANDU nuclear power plants that provide for the design of earthquake resistant nuclear-safety-related structures and components. The National Building Code of Canada has seismic loading provisions for other industrial facilities (including those at nuclear power plants) that are not nuclear-safety related. Application of these existing standards can provide adequate safety during construction, operation, decommissioning and closure of the disposal facilities (Asmis 1981, Asmis 1984).

A survey of the effects of ground shaking at surface due to earthquakes showed that ground motion accelerations less than about $1.9\ \mathrm{m \cdot s^{-2}}$ produce only minor damage to underground excavations (Dowding and Rozen 1978). Provided that seismically active faults are not in the immediate vicinity of the excavated openings, the risk to safety from earthquake damage underground during the construction and operation of a disposal vault would not be significant (Ates et al. 1994).

Seismic zoning maps give a good relative indication of the short-term seismic risk from zone to zone and thus provide a means of directly addressing the AECB's siting guideline on seismic stability. However, they do not provide enough detail to allow meaningful comparison of different potentially-suitable candidate areas within zones. Other factors being equal, areas in seismic zones 0 and 1 are preferable to areas in zones 2 and 3. In addition, candidate areas that are more distant from current clustering of seismic activity, are away from apparent seismically-active faults or ancient rifts, that have a thick crustal plate, or that lack evidence of deep postglacial faulting are preferable.

3.3 MINERAL RESOURCE AND ALTERNATIVE USE POTENTIAL

The occurrence of mineral deposits or other natural resources such as forests or large rivers and lakes in a region is an important consideration in site screening. Past, present and future exploration or exploitation of these resources at the site of a disposal vault could adversely affect the safety of a nuclear fuel waste disposal system. Furthermore, exploitation of such resources may be considered a preferable alternative use of the site. Considerable information regarding the economic mineral, forestry, or hydro-power potential of regions of the Canadian Shield is available from federal and provincial natural resource departments and private mining companies. Recent geochemical maps prepared by the Geological Survey of Canada also outline areas of the Shield with potential for economic mineralization. Some other alternative land uses such as aboriginal territories, heritage sites, wildlife sanctuaries or fragile ecosystems, recreational parks and others are protected by legislation or regulations. These would be identified during the screening process and likely would be excluded from further consideration.

Public participation in formulating screening criteria during the development of the siting process may identify other socially preferable alternative uses for some categories of land in some geographic areas. For example, agricultural use of land suitable for agriculture, and recreational use of land are often considered preferable to other alternative uses that are currently more economically advantageous. The public may also wish to assign values to other surface characteristics of particular sites and these values could change or evolve with time. For example the potential impacts of the project on a local population of animals or plantlife, even if they are not of an endangered species, might need to be assessed.

In addressing the AECB siting guideline on likelihood of resource exploitation, areas of major known economic mineralization, existing mining areas, or areas where future economic mineral exploitation is likely should be excluded during the screening of candidate regions. Areas with less potential for future resource exploitation are generally preferable with two minor exceptions: it is advantageous to have both sufficient water and aggregate resources (sand and gravel) in the vicinity of a potential nuclear fuel waste disposal site for construction and operational requirements (Simmons and Baumgartner 1994).

3.4 GEOLOGICAL SETTING

The regional geological setting includes the different types of soil, rock and sediment at the site (lithology); form, distribution and age relationships; physical and chemical properties, and the type of deformation, especially faulting (geologic structure). The regional geological setting must be understood to determine whether the candidate area contains rock bodies that might be suitable for a disposal vault. The geologic setting also controls the prevalent type of fracturing which must be evaluated to assess the safety and environmental impact of locating a disposal vault in the area.

The geological setting relates the geologic conditions of an area to its location within the overall tectonic and structural framework of the Shield. The tectonic styles and histories of the different tectonic subprovinces of the Shield refer to the combined expression of an array of distinct but interrelated attributes, each of which provides an indication of some aspect of their tectonic evolution (Price and Douglas 1972). For example, if a terrain originated as an island arc of volcanos and sedimentary basins, then was intruded by plutons derived from an oceanic subducting plate, and subsequently was uplifted to expose the deeper, higher-pressure and higher-temperature metamorphosed rocks, a particular suite of rocks will now be exposed at ground surface. These rocks will possess particular structural and lithologic attributes that relate to this geologic history.

The style and the sequence of folding and faulting, relative to the ages of the plutons in the region surrounding candidate area, are also important aspects of the regional geological setting. Elements of the tectonic style that affect the lithologic homogeneity and intensity of fracturing within a pluton and the rock stresses within the pluton include the temperature, pressure, and cooling rates at which different plutons crystallized, and their degree of deuteric alteration and subsequent metamorphism.

The importance of differences in regional tectonic style is highlighted by differences in fracturing and mechanical rock stress that have been observed in the granitic plutons at the Atikokan and Whiteshell Research Areas. These are the Eye-Dashwa Lakes pluton in the Wabigoon subprovince and the Lac du Bonnet batholith in the Winnipeg River subprovince. The differences are ascribed to very different cooling rates for these two intrusions (Stone et al. 1989). The Lac du Bonnet batholith cooled slowly due to its large size and due to the relatively high temperature of the country rock it intruded. This resulted in the development of mainly low-angle thrust faults within an otherwise poorly-fractured granite. In contrast, the Eye-Dashwa Lakes pluton cooled relatively quickly resulting in more and larger (mainly vertical) fractures throughout the pluton. The strong planar mineral fabric within the Lac du Bonnet batholith controlled the location of both the low-dipping and steeply-dipping fractures within the batholith.

In the disposal concept, the geological setting plays an important though indirect role in containing and isolating waste from the surface environment. The degree to which this role can be demonstrated and determined during site screening is somewhat problematic. However, the larger the extent of exposed rock or outcrop, the larger the proportion of the rock that can be either inspected visually or studied by remote sensing methods. This helps geoscientists to determine how complex the rock is and how variable might be the properties of the rock that control the movement of contaminants in the subsurface. Indirect evidence of conditions in the rock is provided by various airborne and ground geophysical surveys and the pattern of the landscape observed on topographic maps, air photographs or satellite images. Lack of significant variations or anomalies in geophysical parameters such as the magnetic, electrical or gravity fields suggests relatively uniform rock properties. A pattern of large linear geophysical anomalies or linear landscape expressions referred to as lineaments, suggests the presence of major geological features such as faults or fracture zones. Mapping exposed rock outcrops and lineament analysis of satellite imagery, airphotos, airborne geophysical data and topographic maps will provide most of the fracture information that would be used for site screening. Areas having fewer major lineaments and having large areas of rock which appear to be uniform and lacking significant faults and fracture zones would be preferred during site screening.

3.5 HYDROLOGY AND HYDROGEOLOGICAL SETTING

Hydrology includes weather and climate, the topography of the land, the occurrence, movement and chemistry of surface water and groundwater, and the relationship between the physical and chemical properties of groundwater and surface water. The hydrogeological setting is the groundwater flow pattern of the area. This includes the rates and directions of groundwater movement and the distribution of groundwater recharge and discharge areas. The hydrogeological setting of the site is important because any movement of contaminants from the disposal vault will likely occur in groundwater within the fractures in the rock surrounding the vault. The groundwater pathways through fractures in the rock will determine the rate and location at which contaminants might migrate from the vault and enter groundwater supplies or the surface environment. During site screening, hydrogeological knowledge will generally be limited by a lack of subsurface information. It is nevertheless possible to make some hydrogeological inferences of candidate areas by studying the topography and the regional surface expressions of fracturing.

In plutonic rocks precipitation generally recharges groundwater through fractures exposed on upland rock outcrops. Water leaves the groundwater regime when it discharges to surface, generally in topographic lows, which are often occupied by swamps, lakes, and streams. Groundwater moves from the topographically high areas to the lower discharge areas because of the differences in groundwater pressure that exist between these areas.

The pattern and rate of groundwater movement and discharge is referred to as the groundwater flow system and it depends on the distributions of permeability, porosity and groundwater pressure within the rock and the amount and consistency of groundwater recharge. Fractures and fracture networks in the rock largely determine the permeability and porosity of plutonic rocks. Large faults or fracture zones are usually the most permeable groundwater pathways in plutonic rock and these control most of the groundwater movement in the rock. Fewer fractures or fracture zones generally imply lower permeability and therefore slower groundwater flow

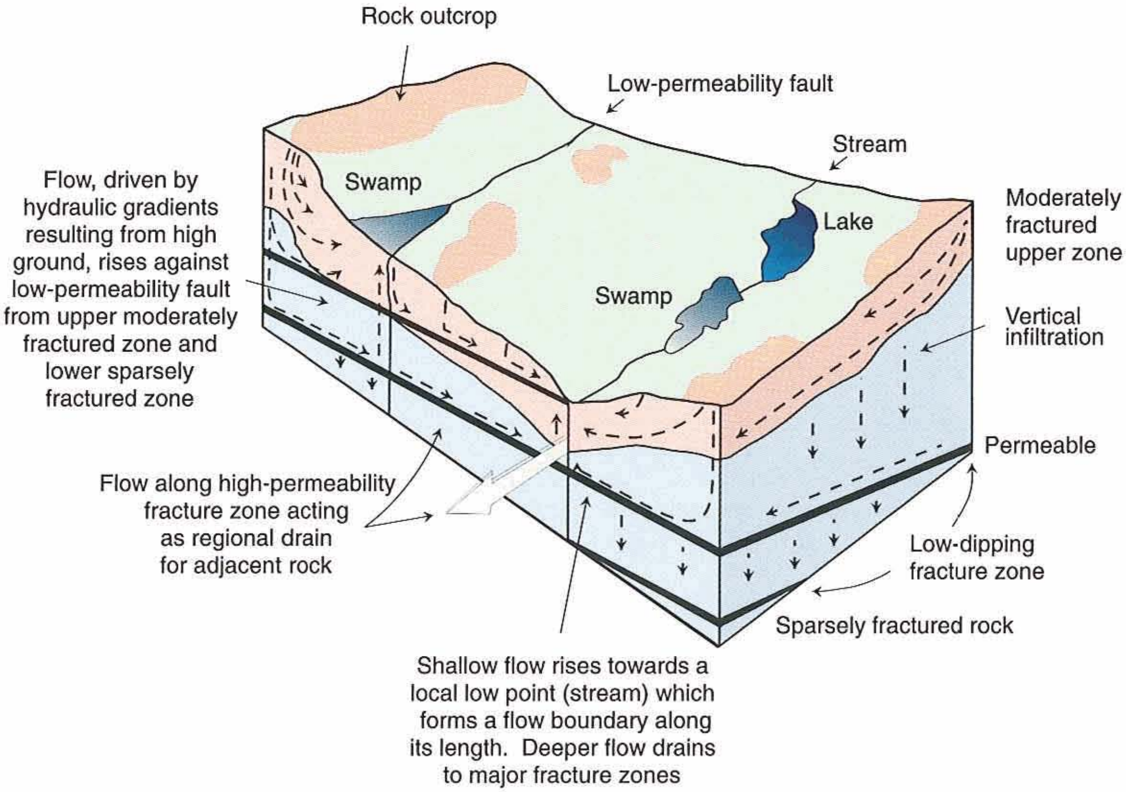


FIGURE 3-4: Schematic of Possible Development of Groundwater Flow Systems in Shield Terrain

through the rock. Flat topography generally results in less variation in groundwater pressure, a lower hydraulic gradient, and therefore slower groundwater flow. Figure 3.4 presents a schematic of the nature of the groundwater flow systems that occur in plutonic rocks of the Shield (after Davison and Pearson 1982).

The groundwater moves through the rock from recharge to discharge areas along pathways in groundwater flow systems that can be classified as local, intermediate or regional depending on the proximity of the discharge area to the recharge location. In this report we refer to groundwater flow systems which are 10 km or greater in length as regional flow systems and flow systems which are 1 km or less in length as local flow systems. Intermediate flow systems are those from 1 to 10 km in length. Relatively flat topography generally favours the development of longer and/or slower groundwater flow paths between the recharge and discharge areas.

Generally, the chemistry of the groundwater depends on the chemistry of the geologic media it flows within and the length of groundwater travel time. More saline groundwaters are usually associated with slower groundwater flow, longer groundwater travel or residence times and longer regional groundwater flow systems. Groundwater chemistry investigations have been performed in deep boreholes at plutonic rock research areas and in mines elsewhere on the Canadian Shield. These indicate that saline groundwater conditions (up to 50 g/L TDS) are likely to exist everywhere in the rocks of the Shield below depths of 500 m to 1000 m (Gascoyne et al. 1987, Frape and Fritz 1987).

During site screening it is possible to make some limited inferences about the groundwater chemistry of an area based on the geological setting and a knowledge of the chemistry of the surface waters of the area. Studying the chemistry of springs and streams during winter or other periods of low flow can provide some knowledge of the chemical conditions of the groundwater. The chloride content is usually a good indicator of the existence and amount of deep groundwater reaching the surface at these locations. Vegetation patterns can also be a useful indicator of groundwater flow conditions. Lower, poorly drained areas are often discharge areas. These areas usually support tree species such as black spruce, tamarack or willow on the Shield. Higher well drained areas are often recharge areas, and these support jack pine and hardwood species such as ash, oak, elm and maple.

Site screening considerations pertinent to hydrogeology include the importance of relatively flat topography, both in terms of low regional topographic slope and low local relief. Within areas of low topographic relief the regional upland areas are preferable because they will tend to be the areas of recharge to the longer and slow moving regional groundwater flow systems. Areas of low local topographic relief also tend to be areas where less fracturing and fewer fracture zones occur at surface, suggesting that they are areas of lower permeability and therefore would have slower rates of groundwater movement.

3.6 DEGREE OF FRACTURING IN THE ROCK

One of the major geotechnical objectives of siting is to select a location for a deep underground disposal facility, in a regional geological and hydrogeological setting, that will inhibit the release, and slow the migration of contaminants from the vault through the surrounding rock to the surface environment. This is largely determined by the degree of fracturing in the rock. A fracture is any break in the rock (whether or not it causes displacement) due to mechanical failure by stress. Fractures include cracks, joints and faults. Fractures can be partly or entirely infilled by high temperature or low temperature alteration minerals. The infilling may have occurred at the time of fracture formation as in dykes where molten rock or other high temperature fluids entered and crystallized at the walls of the fracture, or it may have occurred by minerals precipitating from high to low temperature groundwaters within the fracture. Investigations at field research areas on the Shield indicate that the degree of fracturing is one of the primary distinguishing features between volumes of rock that have significantly different groundwater flow and solute transport characteristics. The different fracture domains that can exist in the rock are:

- fracture zones (faults), which are volumes of intensely fractured rock (usually these can have significant internal variability of solute transport properties);
- moderately fractured rock, which are volumes of rock containing a small number of sets of relatively widely spaced, interconnected discrete fractures (joints); and
- sparsely fractured rock, which are volumes of rock containing microcracks and very sparsely distributed discrete fractures that are not very interconnected; these have fairly uniform solute transport properties.

Although these domains are readily recognizable in boreholes drilled into the rock and in underground excavations, the contacts between them may be gradational and there can be significant differences among them in terms of the degree of internal variability of their hydrogeologic properties and solute transport properties.

We have found that the most important pathways for the movement of groundwater in plutonic rock bodies at the depths of a proposed disposal vault are discrete zones of intense fracturing that cut through the rock and extend or are continuous over relatively large distances. This intense fracturing is concentrated in widely-spaced, narrow zones of usually only a few metres thickness that may extend for distances of several hundreds of metres or even kilometres. These fracture zones may be interconnected with other similar zones that can be either steeply-dipping or low-dipping. These zones are commonly much more permeable to groundwater than the remainder of the rockmass, although significant spatial variations in permeability can occur within them. The permeability variations can cause channel-like patterns of high and low permeability to exist within the fracture zones. Some complex regional faults that are tens of kilometres in length may also be tens to hundreds of metres thick.

Field studies at various research areas on the Shield have also shown that near the ground surface (up to about 200 m to 500 m deep), the rock is also likely to contain networks of individual fractures or joints that are relatively permeable to groundwater. The frequency of these fractures generally decreases with depth. At greater depths (below 200 m to 500 m depth) the rock contains very few permeable fractures aside from the large fracture zones. Figure 3.5 shows a schematic model of this rock structure and illustrates the types of lithologic and structural features that could exist at a plutonic rock site in the Shield. This figure shows the size scale of these features in relation to the size of the conceptual disposal vault and illustrates the groundwater flow conditions that could exist. The figure also illustrates the degree of fracturing associated with the various fracture domains.

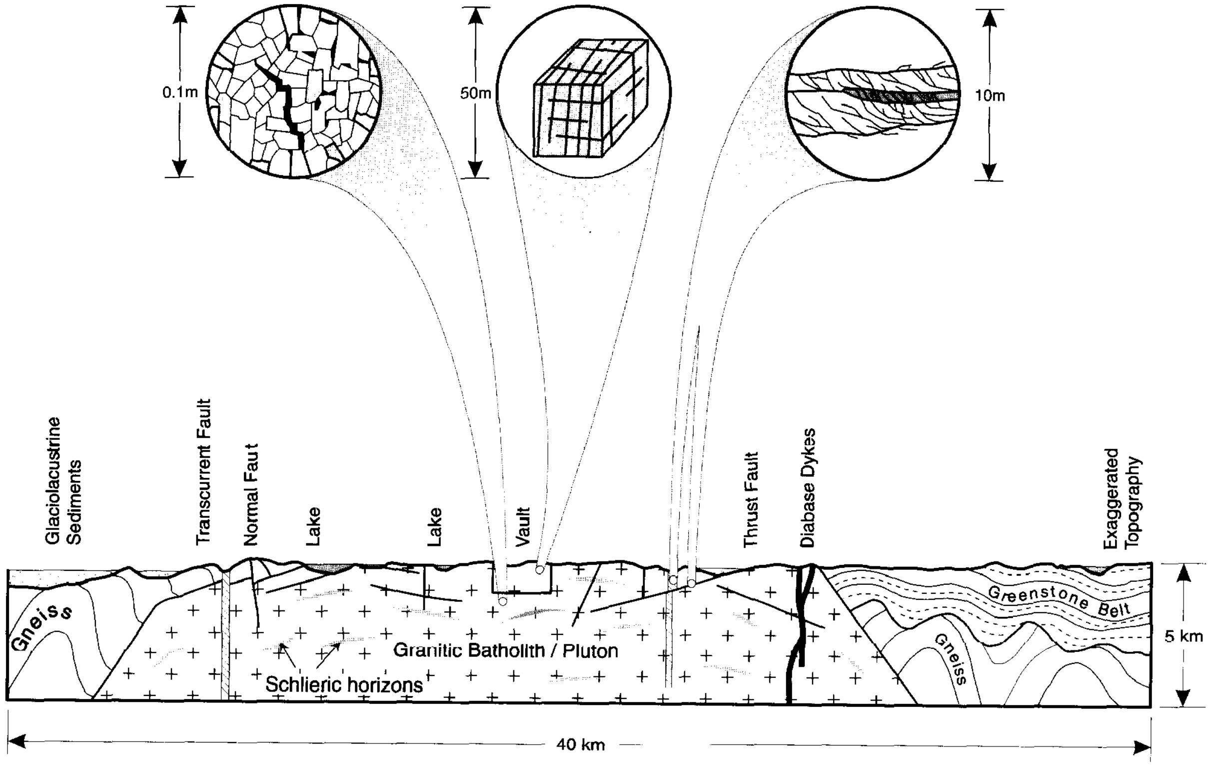


FIGURE 3-5: Schematic of Lithological and Structural Features In and Adjacent to Plutonic Rocks

During site screening it is important to identify features at surface that might indicate the presence of fracture zones in the rock. The potential size and hydrogeologic characteristics of the blocks or volumes of rock bounded by them also need to be estimated.

3.7 SURFACE ENVIRONMENT AND ENVIRONMENTAL SENSITIVITY

Many of the features of the surface environment important to siting are most relevant to and are discussed in the context of the preclosure phases of the disposal project (Grondin et al. 1994). For example, the recognition and avoidance of essential habitat for endangered species would be part of the siting process. This would be an immediate, preclosure concern relevant to the site evaluation, construction and operational phases of the project. However, there are some features of the surface environment that may not influence the preclosure performance of the facility, but that could influence the postclosure performance. In this section, we discuss some of these features and the methods that would be used to integrate these aspects into the overall technical siting process.

To illustrate a feature that may have different implications for pre- and postclosure performance, consider land use capability. Land use capability is an index, based on several landscape characteristics, that reflects the potential for various activities on the land. The activities include agriculture, forestry and recreation, and the relevant landscape characteristics include climate, soil type and depth, drainage and slope. For assessing preclosure impacts, land use will be considered from the perspective that the disposal project should not unnecessarily displace other important land uses such as agriculture and forestry (Grondin et al. 1994). However, with suitable mitigation the disposal project and the other land uses may be deemed compatible during the preclosure phase. In contrast, broad land use capability has different implications in the postclosure phase.

A site with soils or other landscape feature suitable for intensive use by humans and other biota would attract future generations to the site. These future generations represent potential recipients of any long-term impacts from the disposal vault. In this perspective, land use capability is analogous to valuable-ore mineralizations: both may attract future activities that are potentially hazardous. Thus long-term impacts may differ among sites because of features in the surface environment.

The acquisition of data to describe the characterization of the surface environment follows the overall plan of screening followed by detailed site evaluation. During screening, surface environment data would be obtained for candidate areas largely from existing databases, and would be integrated with the aid of a geographic information system (GIS). During site evaluation, more detailed data would be obtained for potentially-suitable candidate areas and sites to assess both pre- and postclosure impacts. Some of the data obtained during site evaluation would be specific to the assessment models to be used. However, much of the surface environment data is needed for both pre- and postclosure assessments. For example, soil types and distributions, surface hydrology, and sizes and flushing rates of water bodies would be required for both pre-and postclosure assessments.

The information required for geotechnical screening and site evaluation also includes information about the surface environment. For example, vegetation, wildlife habits and soil patterns are used as indicators of the surface expression of groundwater conditions as is information about surface water hydrology. Some of this information is also required for assessment of impacts on the surface environment. In turn, information on the potential locations where groundwater from the disposal vault might discharge would direct data acquisition for the detailed site evaluation assessments of the surface environments. Davis et al. (1993) contains a discussion of the surface environment information that would be required for site specific performance assessments.

Environmental sensitivity refers primarily to the susceptibility of the area to environmental damage or disturbance by site characterization activities and by the construction and operation of the waste disposal facilities. This sensitivity to environmental impact pertains to activities common to any large mineral exploration project, civil construction project or underground mining project. Such activities include:

- exploratory borehole drilling,
- clearing vegetation for geological and geophysical surveys and for access roads and constructing surface facilities,
- moving soil and rock, creating substantial stockpiles of broken rock,
- diverting local surface water drainage patterns during the construction of roads, power lines, buildings and the underground excavations,
- disturbing the groundwater regime by drilling and testing exploratory boreholes and constructing of the underground excavations, and
- discharging groundwater at surface during surface-based site characterization activities and during the construction and operation of the underground excavations.

Site screening should give preference to less environmentally sensitive areas that have lower environmental value, and to areas that promise the most scope for locating facilities to minimize adverse impacts on the surface environment.

TABLE 3-1

TECHNICAL FACTORS FOR SITE SCREENING

Screening Factor	Desirable Conditions
Rock mass stability, seismicity/seismic risk	- Seismic hazard zones 0 or 1. - No evidence of postglacial faulting. - Removed from current seismic activity, seismically-active faults, major structural zone contacts or major fault zones.
Mineral resource/land use	- Removed from existing mines, mineral potential, and exploration areas. - No known current valuable mineral resources or likely future resources. - No valuable agricultural, recreational or forestry resources.
Geologic setting	- Large volumes of plutonic rock with uniform properties. - Good rock outcrop exposure. - Few major structural features evident in the rock.
Hydrology and hydrogeological setting	- Low regional topographic slope and low local topographic relief. - Regional upland location.
Degree of fracturing in the rock	- Wide spacing between major structural features in the rock, such as faults and fracture zones. - Fewer fractures, fracture zones or faults evident in the rock between the major features.
Surface environment and environmental sensitivity	- Low environmental sensitivity and value.

3.8 SUMMARY OF TECHNICAL FACTORS FOR SITE SCREENING

Table 3-1 presents a summary of the technical factors that need to be considered during site screening and lists some of the conditions that would be regarded as favourable to the potential suitability of candidate areas for siting a nuclear fuel waste disposal vault. It is evident from Table 3-1 that information regarding the distribution and style of fracturing in the rocks relates to many of the geotechnical factors which would be used for site screening. This is because the potential pathways for the movement of vault contaminants through the rock at the site surrounding the disposal vault are controlled by the fractures in the rock. The location of these fractures and fracture zones and how these fractures interconnect with each other and connect to the surface topography will largely determine the rate and direction of groundwater movement through the rock. The rock mass stability, mineral resource potential, geological setting and hydrogeological setting are all governed to some extent by the distribution and style of the fracturing in the rock.

Most of the important features and processes involved in determining the suitability of a candidate area for siting a nuclear fuel waste disposal vault are related to the potential movement of vault contaminants to the surface environment in the groundwater regime at the site and its surroundings. However investigations of the subsurface to characterize the groundwater conditions will not take place until site evaluation begins. During site screening it is unlikely there will be any significant subsurface geological or hydrogeological information available for most candidate areas. Thus during site screening it will be possible only to infer what the groundwater conditions might be in the candidate regions. These inferences will be based on what can be seen at surface, by extrapolating from the closest location where subsurface information is available and by comparing this information with what has been learned at thoroughly studied research areas located elsewhere on the Canadian Shield.

4. SITE SCREENING METHODS

4.1 INTRODUCTION

In initially selecting plutonic rock as the preferred candidate disposal medium in Canada, the large geographic area of the Canadian Shield with many potential disposal sites was seen as an important advantage in providing flexibility for siting. To benefit from that advantage, from a geoscience perspective, the initial screening phase of siting should identify as many large siting regions on the Shield as possible. This will allow maximum consideration of social and economic factors and other public concerns during the initial screening of these regions to identify a smaller number of potentially-suitable candidate areas that warrant detailed characterization, without any potential compromise of safety considerations or the technical quality of the screening process.

The technical objectives during site screening would be:

- to maximize the size of areas with fewer apparent fractures in the rock and to minimize the level of ambiguity or uncertainty in the identification of these areas;
- to maximize the degree of lithologic homogeneity;
- to maximize the size of the lithologically and structurally homogeneous regions between the major structural discontinuities;
- to maximize the overall distance in the groundwater flow system, that a vault contaminant would have to travel, from a depth of 500 m to 1000 m to reach the surface, and to maximize the time that it would take to travel that distance; and
- to minimize environmentally sensitive or environmentally valuable lands within the siting areas.

Because many of the site screening factors relate to groundwater movement from the potential vault location to the surface environment, and to the degree and style of fracturing in the rock, a major focus of the technical analysis during site screening will be to assess the fracturing of the rock in the siting regions and the potential candidate areas.

During the initial screening of siting regions to identify potentially suitable candidate areas, much of the existing information and many of the criteria can be expressed geographically in map form to show areas that can either be excluded, or are potentially suitable, or that are otherwise ranked in some way. A variety of computer-based geographic information systems (GIS's) are available for this process. AECL recently implemented a GIS system called SPANS which is also used by the Geological Survey of Canada and the Canada Centre for Remote Sensing. SPANS is compatible with GIS systems used by the Ontario Geological Survey and Ontario Hydro (Ejeckam 1992). Geographic information systems would be very useful for a siting process involving continuing public participation because they allow the technical screening criteria and their weighting factors to be changed easily, and the results can be displayed in an easily understandable map form. This would allow all participants in the screening process to compare the results of alternative choices in 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.

During the screening process geoscience and environmental factors would be addressed primarily by analysis of existing regional scale data. A large volume of such information is available as satellite and airborne imagery, airborne geophysical surveys, hydrologic and water resource inventory reports, soils and agricultural reports, vegetation and forestry assessments, surveys of biotic communities, plants and animals (insects, fish, amphibians, reptiles, birds and mammals), inventories of exploratory drill holes or domestic water supply wells, geological reports, and seismic monitoring records. Further reconnaissance geophysical, geological, hydrological, geochemical and surface environment studies would be carried out on the potential candidate areas as needed during site screening to complement this existing data base.

A form of screening was conducted early in the Canadian Nuclear Fuel Waste Management program by Gale et al. (1981) to classify some plutonic rock formations of the Ontario portion of the Canadian Shield with regard to various geological factors that were considered important for siting a nuclear fuel waste disposal vault. This early work illustrates how much reconnaissance geological information was available in 1976. Significantly more information is now available not only from our own investigations of the Shield but also from studies that have been undertaken by other federal and provincial agencies.

Environmental aspects were considered during the site screening for the location of our Underground Research Laboratory near Lac du Bonnet, Manitoba. The report by Pollock and Barrados (1983) describes the environmental screening process that was used. We expect similar environmental aspects would be considered during the screening of a site for an actual nuclear fuel waste disposal vault.

4.2 SATELLITE AND AIRBORNE IMAGERY

Satellite images are available for all of Canada in a variety of formats. Landsat Multispectral Scanner (MSS) imagery provides 80 m spatial resolution and four spectral wavelength bands between 0.50 and 1.10 μm, and 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 surface environment analyses. Good 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. Synthetic aperture radar (SAR) images are available from a recently-commissioned ERS-1 satellite that can provide images of an area from two different scan directions. It has a spatial resolution of up to 12.5 m. This new radar sensor greatly enhances the ability to use satellite imagery to perform geological analysis of structural and lithological conditions of the Shield.

Aerial photography at a variety of scales is available for all parts of the Shield. In addition, Energy, Mines and Resources Canada (EMR) 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. 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 various provincial agencies. EMR has compiled geophysical maps showing the total magnetic field and Bouguer gravity values at the scale of 1:1 million for virtually all of the Shield, and airborne magnetic data are generally available at scales of 1:250 000 and 1:50 000 for most of the Shield. Airborne electromagnetic (EM) and gamma-ray spectrometry data also are available for many areas of the Shield from EMR, OMNR and from provincial mining or geological agencies.

One of the major uses of remotely-sensed data surveys such as airborne magnetics, satellite spectroscopy, synthetic aperture radar and aerial photography is to identify linear anisotropies which may represent features such as dykes, faults or fracture zones. This allows ground-based data to be extended to areas not traversed during mapping, assists the possible identification of faults or fracture zones in areas of little or no outcrop, and permits the identification of features too large to be recognized during ground-based mapping. Airborne magnetic surveys are discussed later in Section 4.4.1 because they are largely a site evaluation method.

We have been using linear structures (lineaments) identified from Landsat Thematic Mapper (TM) spectral bands 1-7 and from Ministry of Energy, Mines and Resources black-and-white airphotos at 1:50 000 and 1:15 840 scales to help locate and map likely fracture zones and faults in the rocks at our research areas and study areas on the Canadian Shield. Lineaments from Landsat TM are identified by inspection on the computer screen, in cases where digital data are available, and these are then transformed into computer files. Where digital data are not always available for computer-assisted processing, as in the case of airphotos, the lineaments can be initially identified on the photographic image by visual inspection and then compiled in a lineament mosaic, which can be subsequently digitized and entered into a computer data base.

Recent advances in personal computer technology now enable geoscientists to work directly with the Landsat and other remote sensing data 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 data sets. AECL recently acquired the computer capabilities to manipulate these types of data sets and has 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 (Good and Brown 1991). Remote sensing data sets, GIS data and automated map production techniques have been fully integrated by AECL. This allows the rapid preparation of base maps and geologic interpretations from the different sources of reconnaissance data.

After the data base of lineaments has been assembled, their orientations, spatial frequency distributions, length distributions, geometric shape, and association with particular tectonic or lithologic terrains can be examined. If ground-based mesoscopic fracture frequency data are available from the reconnaissance mapping of rock outcrops, it can be entered into a GIS database and used with the lineament maps to establish if any relationships exist between the fracture data and any of the lineaments or sets of lineaments. Then lineaments of various sizes can be ranked as to their probability of being faults. Examples of this type of lineament analysis are contained in the reports by P.A. Brown et al. (1980b), P.A. Brown et al. (1982), P.A. Brown and Rey (1982), McCrank et al. (1983), McCrank (1985), Good (1990) and, Good and Brown (1991). The earlier analyses were manual. Recent analyses have been performed using much more rapid computer-assisted methods.

4.3 GEOLOGICAL REPORTS

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

The Ontario Geological Survey has recently published a two-volume report on the geology of Ontario with a boxed set of thirty-four maps and charts including 1:1 000 000 scale maps of bedrock geology, shaded total magnetic field, vertical magnetic gradient, Bouguer gravity field, shaded vertical gravity gradient, Quaternary geology, and tectonic assemblages. The first volume (Thurston et al. 1991) deals with the geology of the Superior Province, the Southern Province and discusses Proterozoic events; the second volume (Thurston et al. 1992) deals with the geology of the Grenville province, discusses Phanerozoic and Quaternary events and contains a metallogeny and tectonic summary for the entire province of Ontario. In addition, the second volume contains a discussion of the U-Pb geochronological framework for the western Superior Province, (Corfu and Davis 1992),a very useful resource for any new geologic studies of this portion of the Shield.

Also, The Ontario Geological Survey has recently completed mapping the geology of the 30 000-km^2 segment of the Berens subprovince of the Superior Province in Northwestern Ontario. The terrain of the Berens subprovince is dominated by a variety of granitic plutons and is delineated on the basis of pluton composition, texture and relative chronology. This project was started by the Ontario Geological Survey in 1989 and the field work was completed during 1993.

The Canadian Lithoprobe program has recently undertaken two multidisciplinary projects on the Shield. These have involved geophysical surveys, geological studies and seismic reflection profiles in the areas of the Kapuskasing Structural Zone and Abitibi-Grenville front to provide information on geologic structures that exist in the crust at depths up to 30 km in these two areas (Boland and Ellis 1991, Milkereit et al. 1991, Milkereit et al. 1992).

Another Lithoprobe project is due to commence on the Shield in 1994 along the Ontario-Manitoba boundary in the Superior Province. This project should provide further information on deep crustal structures in the Shield (Clowes 1993).

The Geological Society of America's Decade of North American Geology project (DNAG) has compiled some useful information on the rocks of the Shield. Comprehensive volumes have been produced involving reviews of existing information, new interpretations and compilations of recent developments in all aspects of the geosciences. Volumes containing information of particular relevance to the Shield are an overview of the geology of North America (Bally and Palmer 1989) and the Superior Province of the Shield (Card and Ciesieleski 1986), and volumes on neotectonics (Slemmons et al. 1991), hydrogeology (Back et al. 1988), surface water hydrology (Wolman and Riggs 1990) and the last deglaciation (Ruddiman and Wright 1987). These volumes contain very extensive lists of references dealing with the Shield.

In conjunction with DNAG, the Geological Survey of Canada is publishing an update of the geology of Canada in several volumes. The only volume relevant to the Shield that has been published so far deals with Quaternary geology (Fulton 1989). A summary volume on the geology of Canada and volumes on the Precambrian geology and economic geology should be available soon.

Considerable information is also available from various federal and provincial departments about climate, surficial geology, soils, surface water hydrology and hydro-power potential, 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.

Evaluation of this existing information during site screening, after initial potential candidate areas have been identified, will emphasize identification of: areas having relatively large plutonic rock bodies (several hundred square kilometres or larger), areas having flatter, upland topography, areas that appear to have few structural discontinuities (fractures) and, areas that appear to have relatively uniform geological properties.

A potentially suitable candidate area would cover in the order of several hundreds of km^2 (about 400 km^2). Site screening is designed to provide the information needed to select a small number of potentially suitable candidate areas for subsequent site evaluation studies. Surface and subsurface characterization of potentially-suitable candidate area would be done during site evaluation to provide sufficient information to properly locate a suitable candidate site for the vault within the large scale geological and hydrogeological setting of the candidate area. This candidate site (about 25 km^2 in size) would require very thorough surface and subsurface characterization before the final location for the disposal vault (approximately 2 to 4 km^2 in plan area) could be identified.

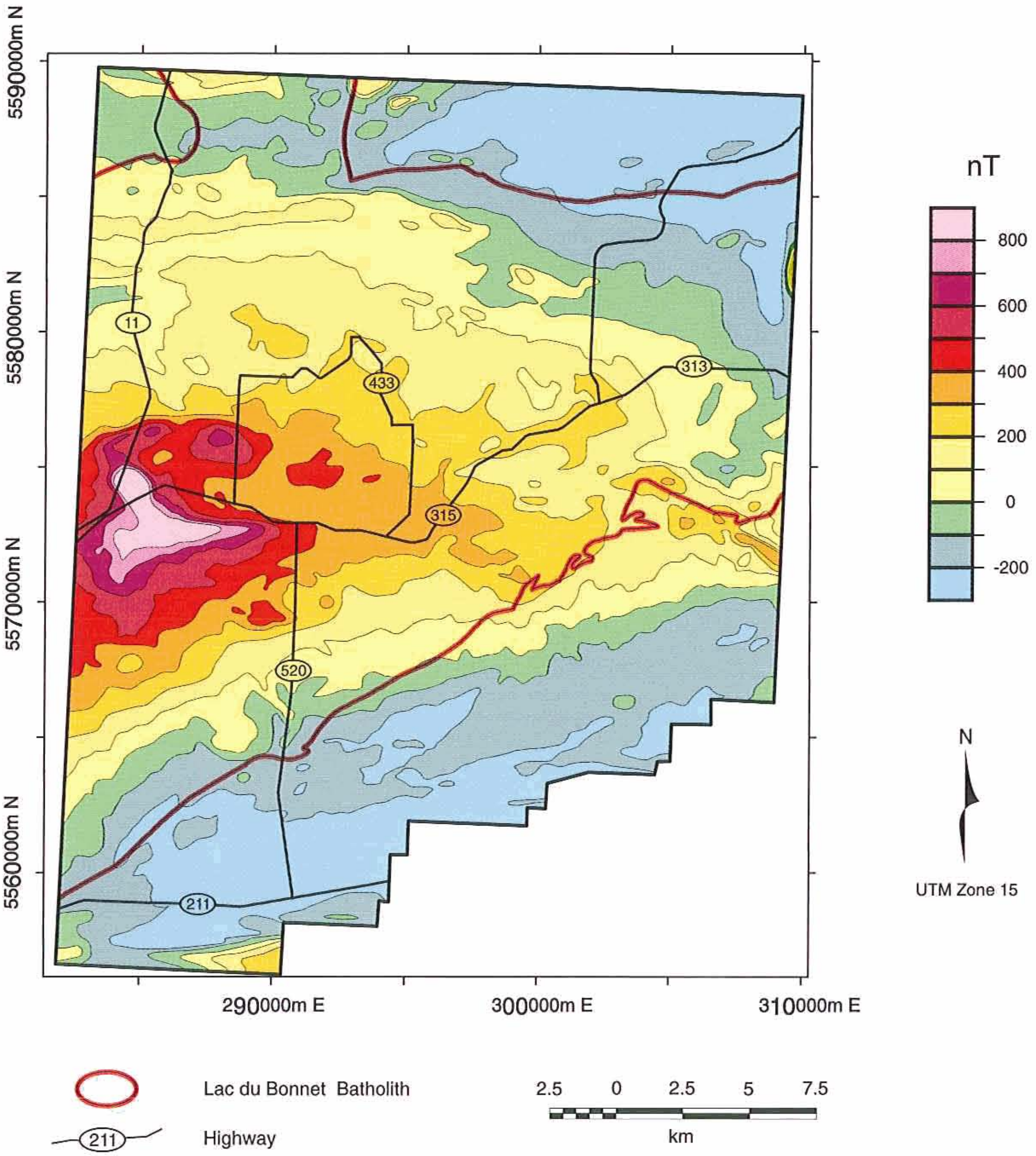


FIGURE 4-1: Residual Magnetic Field Map of the Whiteshell Research Area

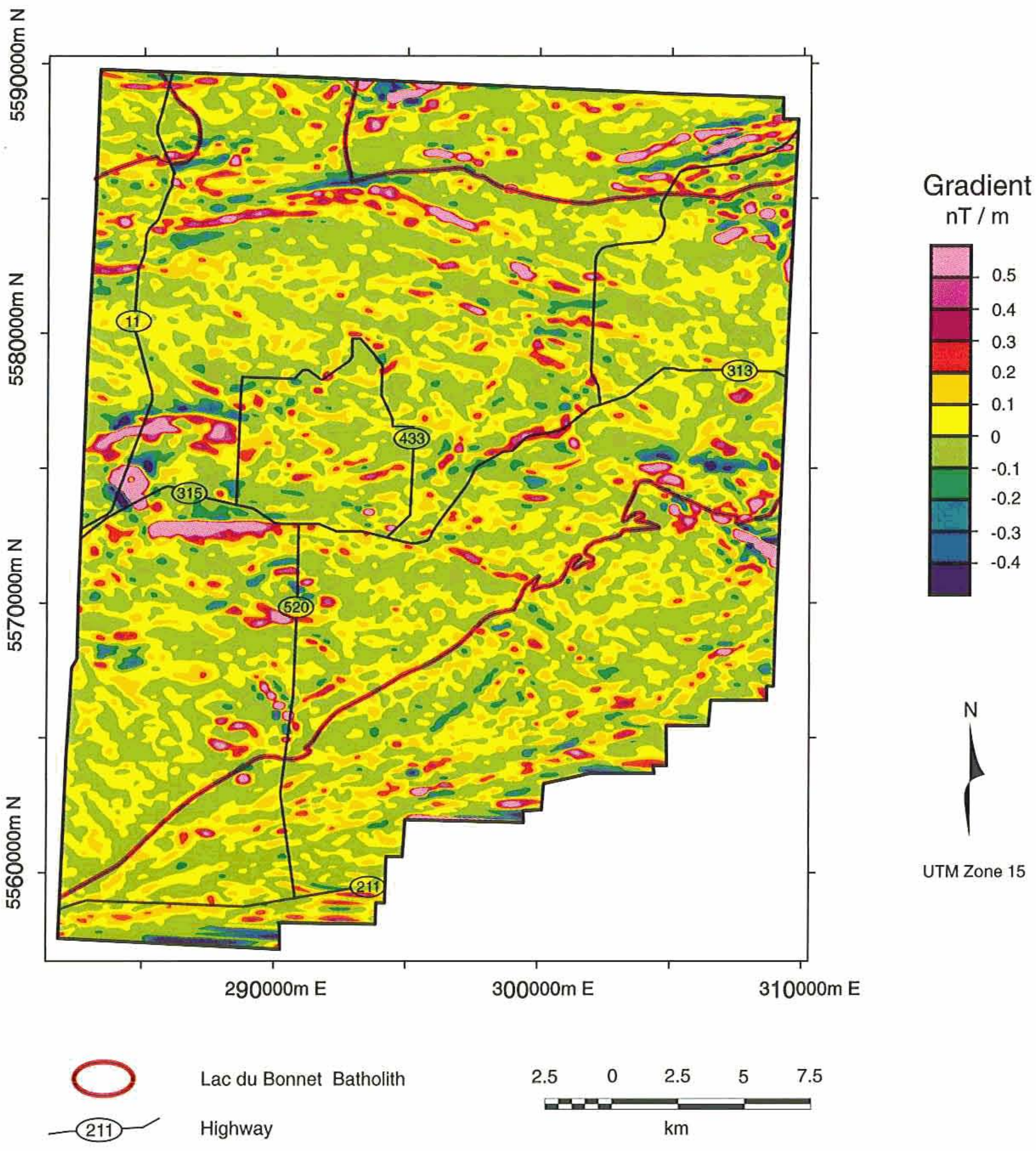


FIGURE 4-2: Vertical Magnetic Gradient Map of the Whiteshell Research Area

4.4 RECONNAISSANCE INVESTIGATIONS DURING SITE SCREENING

Site screening mainly involves the office compilation of existing information and data from the wide variety of sources described above. However some field investigations using geophysical, geological, hydrological, geochemical and surface environment methods would also be carried out during this phase to verify the existing data, obtain additional data, and confirm the office interpretations. These reconnaissance field investigations would be performed by conducting selected airborne surveys of the regions surrounding the candidate areas and conducting subsequent ground follow-up studies using access provided by existing roads or trails, navigable waterways, helicopters or float planes.

4.4.1 Geophysical Methods

Maps of the existing reconnaissance geophysical surveys were compiled at the beginning of our investigations at the Whiteshell Research Area (Lac du Bonnet Batholith), the Atikokan Research Area (Eye Dashwa Pluton) and the East Bull Lake Research Area (East Bull Lake Pluton). These serve as good examples of how such reconnaissance information would be used during site screening to identify and delineate plutonics rock bodies, to assess their homogeneity, to determine their geological setting and to determine fracture characteristics. Airborne radar, magnetic, gravity, radiometric and electrical survey data all provide useful reconnaissance information. A few examples are presented below as illustrations.

Aeromagnetic Surveys

A map of the total aeromagnetic field of a 900 km^2 area of the Whiteshell Research Area in southeastern Manitoba (Figure 4.1) clearly shows the outline of the granitic Lac du Bonnet batholith as a distinct region of high magnetic field. For comparison, the boundary between the batholith and the adjacent rocks, as determined by geological mapping, is also shown.

Aeromagnetic survey data from two magnetic sensors can be processed to produce vertical gradient maps which are useful in identifying the structure and lithology and in evaluating the homogeneity/heterogeneity of plutonic rock bodies and their surroundings (Soonawala 1984, Gibb and Scott 1986, Soonawala et al. 1990). For example the vertical magnetic gradient map of the Whiteshell Research Area (Figure 4.2) shows that higher or lower magnetic gradient values are sometimes aligned to produce magnetic lineaments. On further examination, many of these magnetic lineaments have similar geometric orientations which are often consistent with observed orientations of lithological variations or structural features in the rock such as fracture zones. Three distinct orientations of magnetic lineament trends are observed on Figure 4.2: ENE-WSW, ESE-WNW and NNE-SSW.

The ENE-WSW trend is roughly parallel to the longitudinal axis of the batholith. This trend is weak within the batholith but is very well

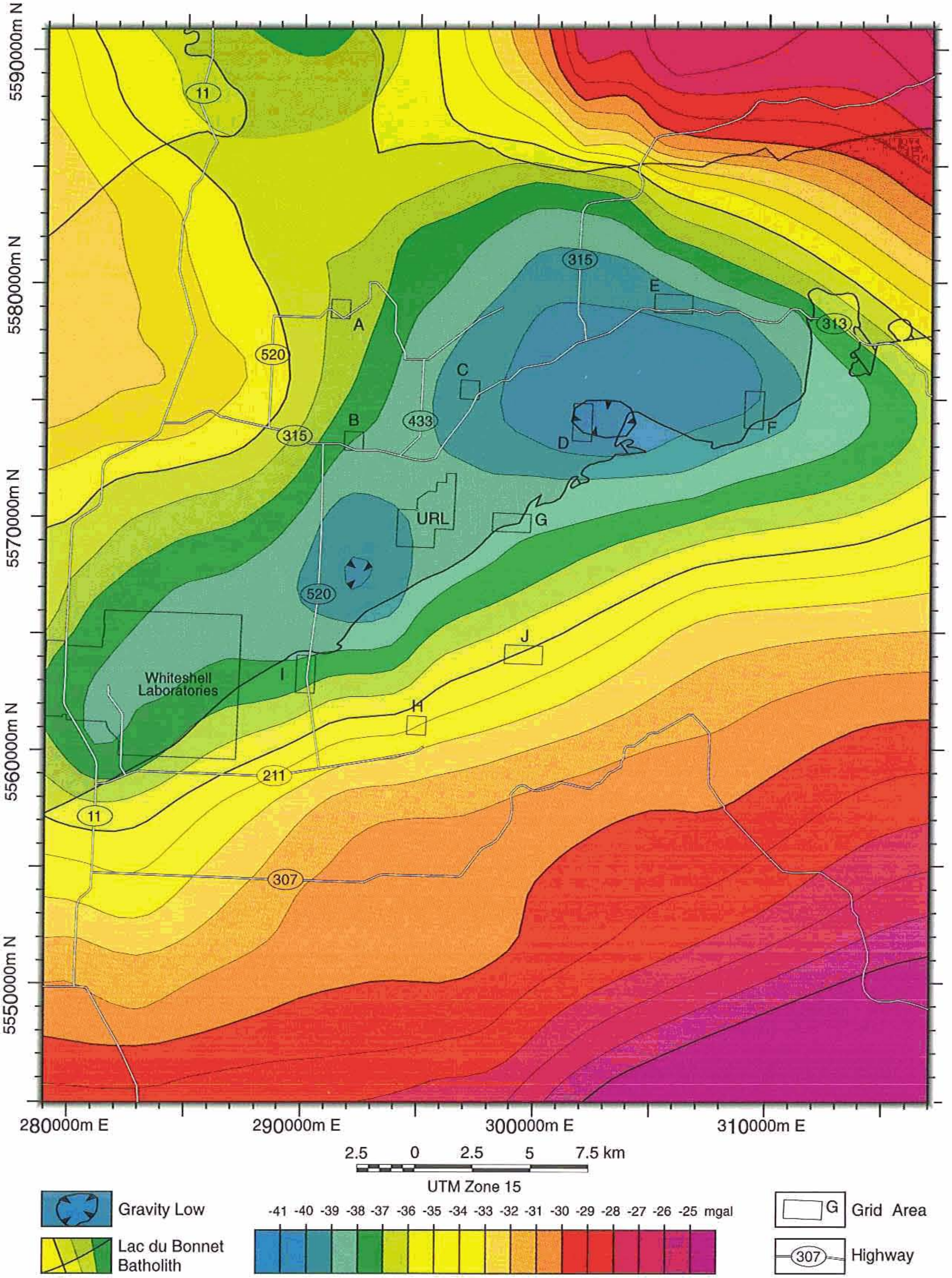


FIGURE 4-3: Gravity Map of the Whiteshell Research Area

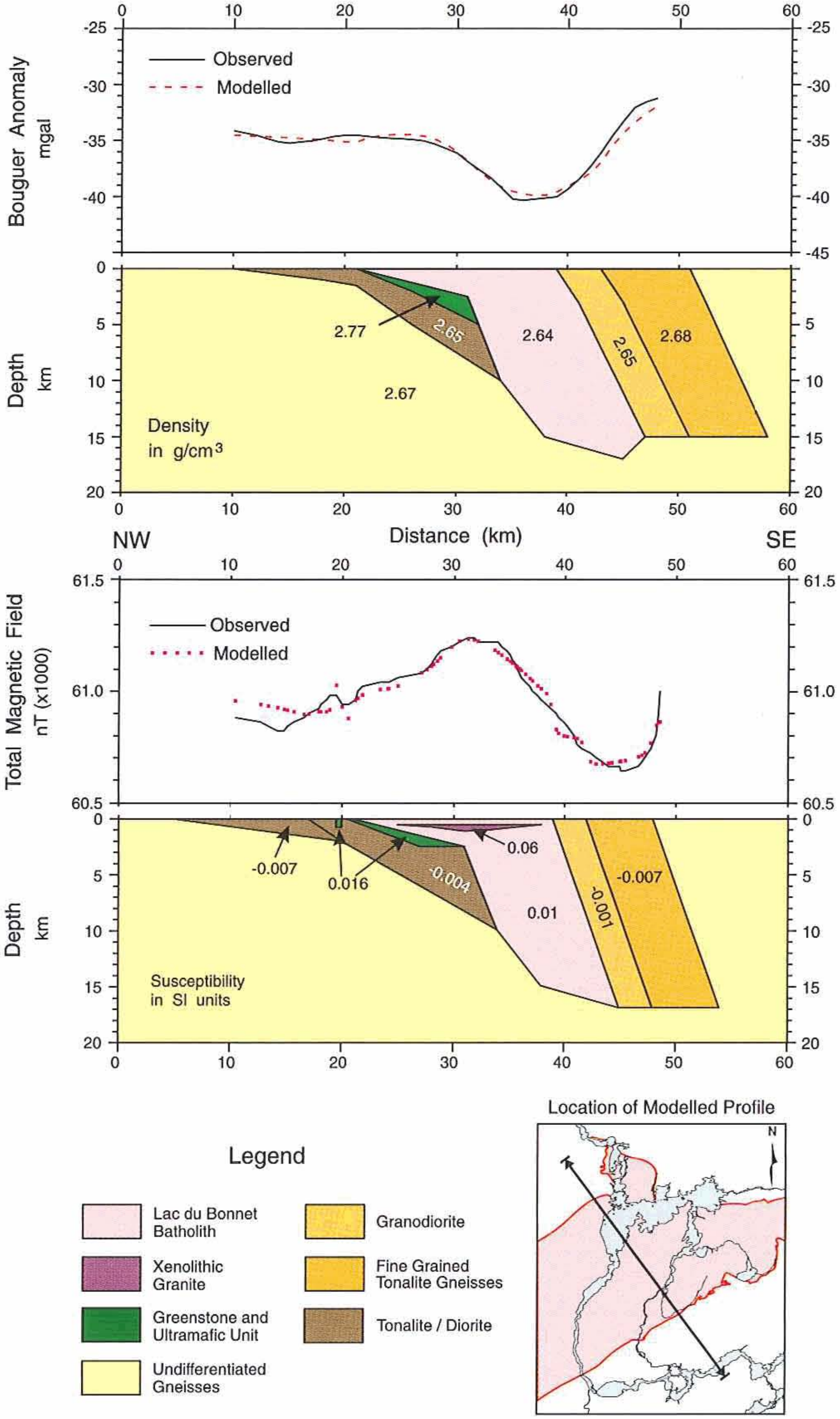


FIGURE 4-4: Subsurface Models of Gravity and Magnetic Data - Whiteshell Research Area

Radiometric Surveys

Granitic rocks are generally enriched in the naturally occurring radioelements uranium, thorium and potassium. Therefore granitic plutonic rock bodies can often 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 1970s provides an excellent database for the construction of regional radiometric maps or profiles.

Figure 4.5 is an 80-km long section of a radiometric profile which crosses the Lac du Bonnet Batholith near its eastern boundary. The profile shows the enhanced radioelement concentration over the batholith compared to the surrounding rocks. The second high radiometric anomaly along this profile corresponds to an adjacent granitic batholith, the Whiteshell Batholith.

Electrical Surveys

Electrical survey methods are widely used to determine features of the surface and subsurface geology by mapping variations in the electrical conductivity of the ground. In Shield terrain such variations can be caused by changes in the thickness and lithology of overburden materials, fracturing in the rock (vertical or dipping), mineralized zones, 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 to depths ranging from a few metres to a few kilometres during site screening (Gibb and Scott 1986, Soonawala and Hayles 1986, Soonawala et al. 1990). These include:

- airborne surveys in the electromagnetic (EM) frequency range of 1 000 to 32 000 Hz using multifrequency coaxial or coplanar coils,

- airborne surveys using radar energy,

- airborne electromagnetic surveys at very low frequency (VLF) (~24 kHz) to measure the response to signals generated by remote naval communications transmitter stations, and

- 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 for mapping the distribution and thickness of unconsolidated overburden deposits 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. These surveys were found to be effective in mapping the distribution and thickness of the

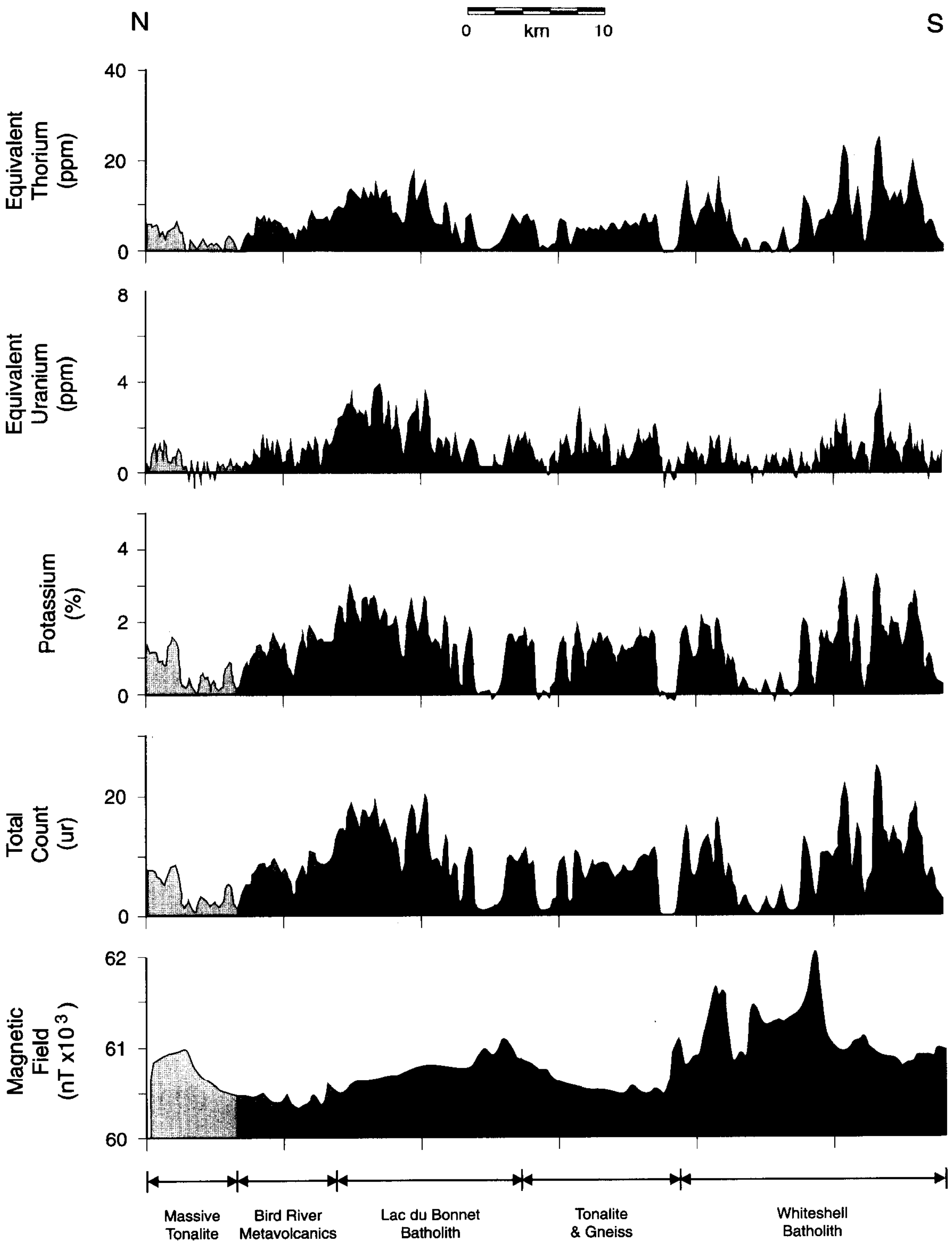


FIGURE 4-5: Radiometric Profiles Across the Whiteshell Research Area

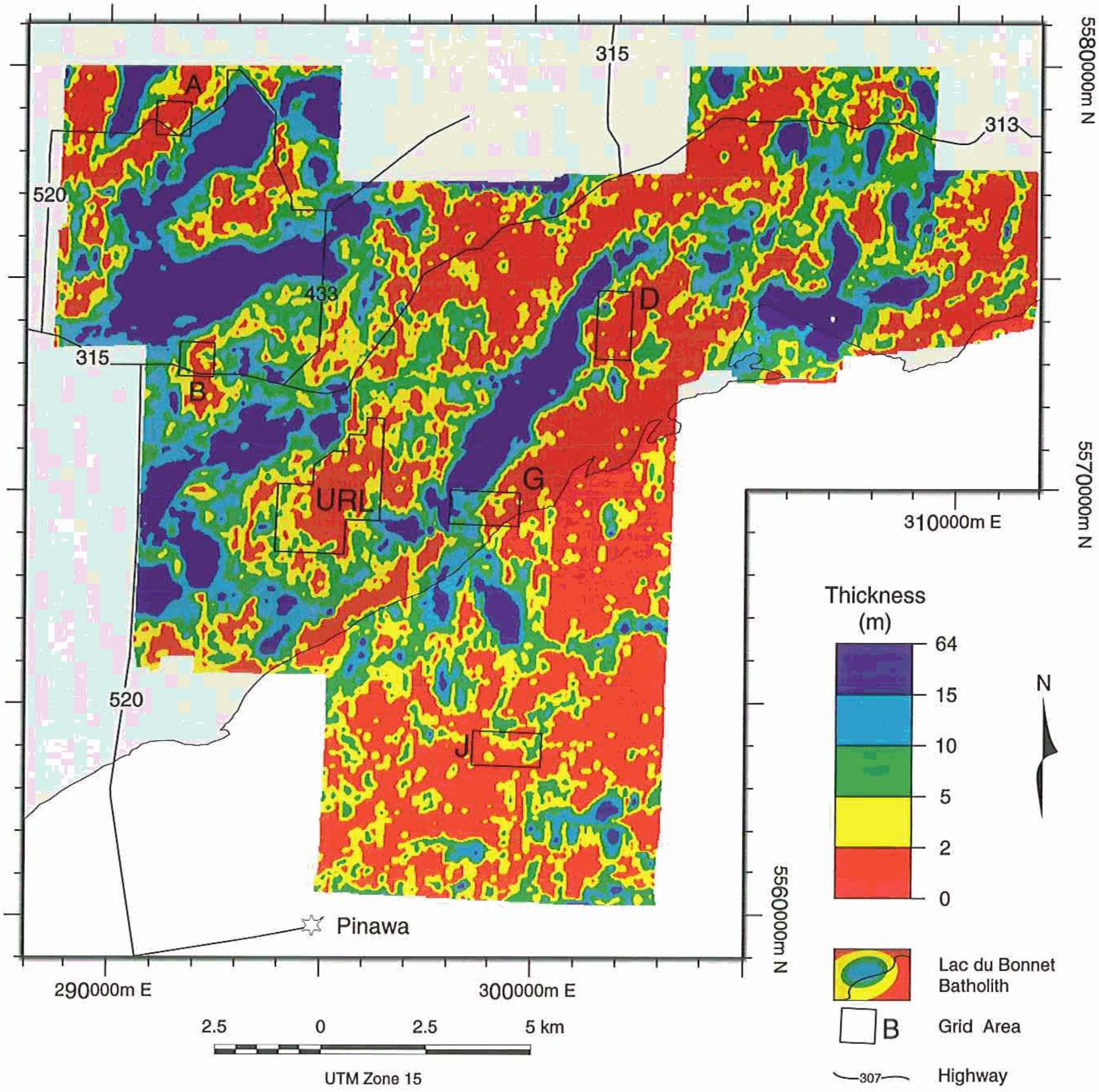


FIGURE 4-6: Overburden Thickness Map of the Whiteshell Research Area as Derived from Airborne VLF-EM

overburden deposits at the Whiteshell and Atikokan Research Areas (Soonawala et al. 1990, Seebrook and Hall 1989, Soonawala 1994a, Soonawala 1994b).

An overburden map produced from airborne geophysical surveys for a portion of the Whiteshell Research Area is shown in Figure 4.6. In general the thickness of overburden varies between 0 to 4 metres over most of this area. However, areas which correspond to the locations where major fracture zones in the rock come to surface show up as sediment-filled linear valleys on this map, with overburden thicknesses varying from 4 to 20 metres. Beneath the major river systems and lakes in the Whiteshell Research Area the overburden thicknesses are often in excess of 20 metres and occasionally appear to approach 60 to 80 metres.

Ground EM surveys, involving multifrequency horizontal loop systems like Geonics EM-36, MAX-MIN, and resistivity soundings are useful reconnaissance methods to differentiate-sediment layering within the overburden deposits (Soonawala 1984). This mappable layering is caused by changes in soil structure, clay content, conductivity or salinity of the soil water and 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. For instance, 1 to 2 m thick low-dipping fracture zones can be traced in granitic rocks to a depth of 60 to 80 metres below outcrop surfaces using surface radar surveys (Stevens et al. 1994, Holloway et al. 1993). Other shallow-penetrating electrical methods will map these fracture zones only if they are more than about 2 metres thick and have an areal extent of several hundred square metres. Fracture zones which intersect the surface and which exceed about 5 metres in thickness with a larger areal extent can be detected by almost all of the reconnaissance electrical survey techniques so long as the overburden is not too thick (Soonawala 1984).

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 dipping 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 EM energy the deeper the survey can penetrate. However, for the 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. Although the deep penetrating electrical surveys have the theoretical potential to identify major fracture zones at great depth, features observed in survey data have not been confirmed because we have not drilled deeper than 1200 m at our research areas. Furthermore, the poor resolution of these methods to a depth of 1000 m in comparison to other methods limits their practical usefulness in site screening and site evaluation.

High resolution, high frequency seismic reflection surveys can be useful in mapping 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, Kim et al. 1994). However, variations in the fracture zone thickness may produce discontinuous reflections. For the relatively high frequency seismic signal of 100 Hz, the quarter wavelength is 15 m in granite of velocity 6000 m/s. This implies that portions of fracture zones thinner than 15 m in the rock can probably not be detected as continuous seismic reflectors using seismic reflection surveys. Significant research on applications of high resolution seismic surveys for mapping deep lithological and structural changes in rocks of the Shield is currently being done under the National Lithoprobe program and has led to enhancements in the ability of these methods to detect deep subsurface fracture zones in these terrains (Clowes 1993).

Table 4-1 lists the geophysical methods that would be useful during site screening. When used in combination, and with information from complementary satellite imagery, airphotographs and reconnaissance geological mapping, these geophysical surveys provide a great deal of information on the shape, size, structure, lithology and geologic setting of plutonic rock bodies in Shield terrains (Gibb and Scott 1986, Soonawala et al. 1990).

TABLE 4-1

GEOPHYSICAL METHODS USED DURING SITE SCREENING

Method	Information Provided
Airborne EM and VLF-EM	Lithologic variations, location of large structural features such as faults and fracture zones, overburden distribution and thickness.
Aeromagnetic	Shape, depth and boundaries of pluton, surface and subsurface distribution of large lithologic variations, identification of lineaments caused by lithology or large geologic structures.
Airborne Radiometric	Boundaries of pluton.
Gravity	Shape, depth, boundaries of pluton and surrounding rock units.
Surface Electrical	Large scale geologic structures, lithologic contacts, location of possible major fracture zones.
Reflection Seismic	Large fracture zones and lithologic variations in subsurface.

4.4.2 Geological Mapping Methods

Although a large amount of useful geological information already exists in the form of available geological reports and maps for screening regions of the Canadian Shield for nuclear waste disposal, some reconnaissance geological mapping would be necessary during site screening to obtain additional regional geological information for particular candidate areas of interest. This additional geological information would be used to augment and verify the geological information contained in existing reports and data files.

During our research program we have carried out two such reconnaissance geological mapping studies: one involving the geologic comparison of five granite intrusions located in the northwestern Ontario portion of the Shield (McCrank et al. 1994a); and the other involving the comparison of five gabbro plutons, four located in northwestern Ontario and one located between Elliot Lake and Sudbury, in north central Ontario (P.A. Brown et al. 1980a, Kamineni et al. 1992). Figure 4.7 shows the locations of these rock bodies.

The first step in these reconnaissance geological studies would involve a brief (one-half day to one day) fly-in visit to the region of each candidate area by a small team of geologists and hydrogeologists to assess the following conditions:

- accessibility for work, (roads, terrain, etc.),
- outcrop density,
- lithologic properties and information in existing maps and reports, and
- fracture density at selected outcrops.

The geological information obtained during these brief visits would be combined with a preliminary analysis of large scale faulting evident from airphoto lineament analysis, satellite radar and spectral image analyses, reconnaissance geophysical surveys, and maps of hydrological drainage catchments. This would be used to assess the suitability of each potential candidate area for conducting additional, more detailed ground mapping. Examples of such an assessment are Gale et al. (1981), P.A. Brown and Thivierge (1981), P.A. Brown (1981), McCrank et al. (1983) and P.A. Brown et al. (1980a).

Following this initial reconnaissance study, more detailed geological ground mapping surveys could be planned at the candidate areas. These follow-up geological mapping surveys would involve about ten days of field inspection at each location to determine:

- outcrop density, distribution and quality,
- location, character and spatial distribution of rock types in the area,
- mesoscopic fracture characteristics and their relationship to the lineaments evident on reconnaissance geophysical surveys, airphotos and satellite imagery, and
- indicators of the tectonic history of the lithology and fracturing.

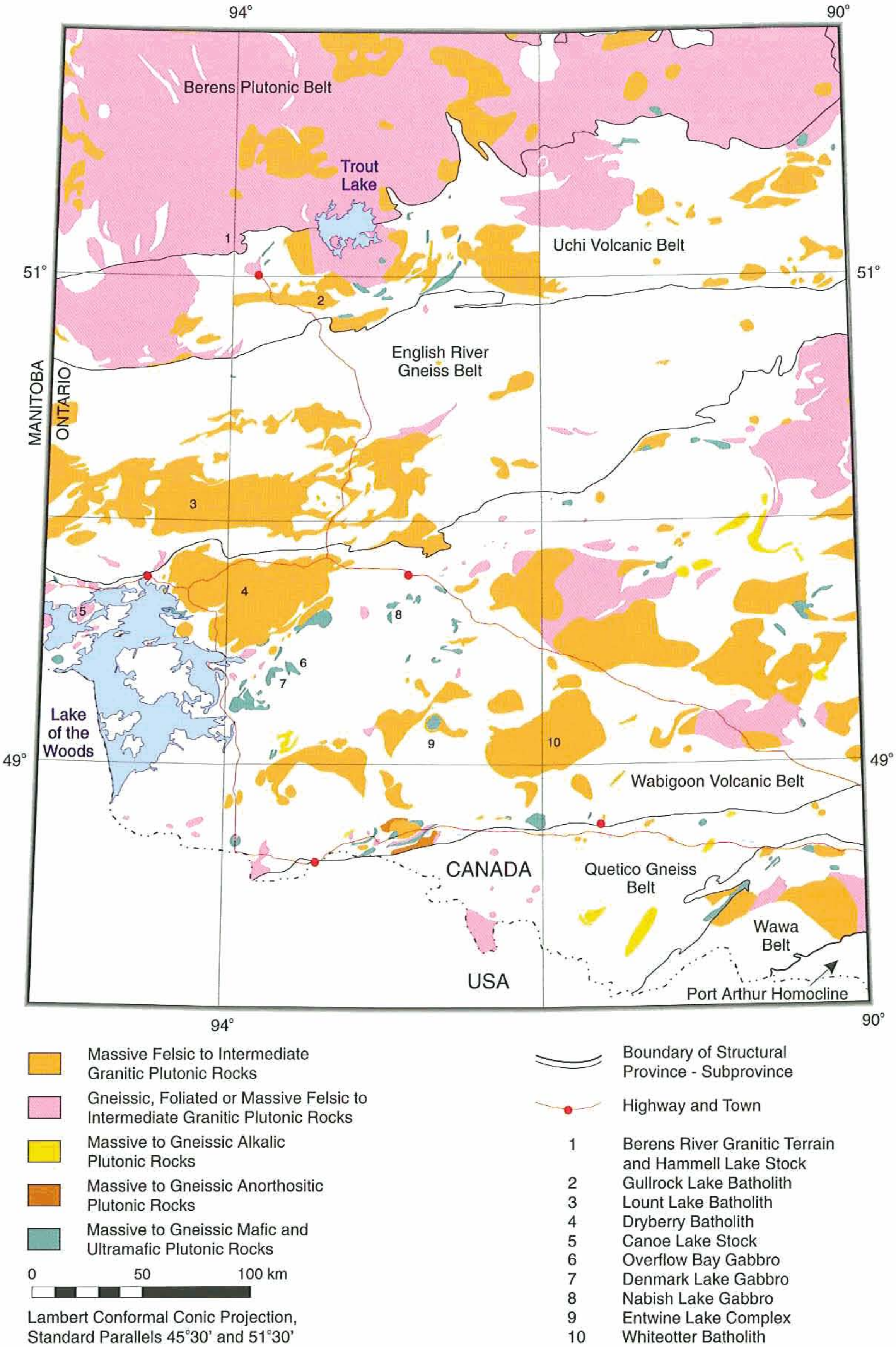
In the office, the geological information collected from these follow-up reconnaissance field mapping surveys would be combined to assess the geologic significance of the lineaments identified on airphoto and satellite imagery and linear geophysical anomalies. Of particular importance would be the potential for them to be major fracture zones. In addition, the fracture characteristics of the rocks between the major features would be compiled and displayed on maps. These maps would include information on fracture frequency, fracture orientation and the age relationships of the fractures.

The report used to select the East Bull Lake gabbro pluton as one of our research areas (P.A. Brown et al. 1980a), is a good example of such a reconnaissance geological study. A similar but slightly more detailed methodology was used by McCrank et al. (1994a) to examine five granite plutons in the Superior Province, to compare granitic intrusions in different Shield subprovinces.

4.4.3 Hydrological Methods

Reconnaissance surveys would be conducted during site screening to obtain hydrologic information. These would involve initial aerial inspection surveys, either by helicopter or fixed wing airplane with brief field inspections. This would provide a basis to make decisions about any subsequent and more detailed field investigations of the hydrological conditions. These brief field surveys would be used to inspect and verify important topographic and hydrologic features, such as expected groundwater recharge and discharge areas, which would have been identified from air photographs, satellite images and topographic maps.

Additional field inspections might be necessary to evaluate such features as topographic divides of major watersheds or tributary catchments to examine potential locations for hydrometric monitoring stations. These inspections would also provide a reconnaissance assessment of the hydrologic conditions of the region such as the range of surface water flows, surface water level fluctuations and accessibility of potential sites for longer term routine monitoring. As part of these initial hydrologic surveys attention would be given to assessing general field



Adapted from Source Map Compiled by G.F.D.McCrank, J.D.Misiura and P.A.Brown (1979)

FIGURE 4-7: Location of Reconnaissance Mapping Projects conditions and determining the methodology, instrumentation and equipment that would be required for any subsequent detailed studies of the hydrologic conditions.

Some hydrogeologic observations would also be made during these brief reconnaissance field visits. Surficial geological deposits and rock outcrops would be examined for hydrogeological features to obtain an initial idea of groundwater movement within the candidate region. Surface indicators of groundwater discharge would be examined to provide information about the storage and permeability of the surficial deposits or rock. For example, springs and seeps indicate discharge areas of local or larger groundwater flow systems. Estimates of discharge rates and measurements of the water chemistry of these springs and seeps would provide information to assist in an initial hydrogeologic assessment. Similarly studies of vegetation patterns or animal behaviour patterns can indicate the locations of groundwater discharges and can sometimes reveal information about the salinity of the discharging groundwater (Stephenson et al. 1992).

4.4.4 Geochemical Methods

Knowledge of the geochemical characteristics of groundwater in a candidate area would be obtained during site screening by compiling existing water quality information for domestic water supply wells or surface water bodies in the region. A study of this information would yield useful insight into the location and chemical character of groundwater discharge areas. For example, Gascoyne and Elliot (1986) used provincial government records of water quality information for domestic water supply wells to examine the chemistry of shallow groundwaters in the rocks and sediments of the Whiteshell Research Area. In turn, this information allowed them to determine the relative amount of deep saline groundwater that might be discharging from the rock into the shallow groundwater regime.

Reconnaissance studies of the spatial and temporal variations in the ionic content of the surface waters in a candidate area can provide information about groundwater discharge areas because discharging groundwaters often have a chemical composition that is quite distinct from that of surface water. Some chemical methods used to identify 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. 1994), and using airborne or satellite thermal infrared imagery to detect anomalous patterns in the temperature of surface waters (Lee and Tracey 1984).

The locations of discrete discharges of saline groundwater at the surface can sometimes be detected by conducting reconnaissance chemical sampling surveys of the surface waters or by examining the feeding patterns of large ungulates (moose and deer). Localized occurrences of anomalously high levels of dissolved salts in surface waters and soils are well known to attract such animals. Some examples of these occurrences (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 surface waters near 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. 1993b).

Recently, a soil gas measurement technique has been developed which can be used to detect locations where deep groundwater might be discharging from subsurface bedrock fractures. Although the method is probably most suited to the scale of investigations that would be conducted during site evaluation, it could also be used as a reconnaissance method during site screening. The technique involves the analysis of the content of the dissolved gases radon and helium in the soils overlying the bedrock (Gregory and Durrance 1987, Banwell and Parizek 1988, Gascoyne and Wuschke 1990, Gascoyne et al. 1993a). Radon and helium are gases that are produced in bedrock by the radioactive decay of naturally occurring uranium and thorium bearing minerals. These gases can diffuse from the minerals, dissolve in groundwater and migrate to the surface where they enter overlying water bodies or soils. At the Whiteshell Research Area, natural anomalies in radon and particularly helium have been identified in the soils and surface waters which are situated in an area where groundwaters from deeper, large scale flow systems have been discharging to ground 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, saline flow system (Gascoyne et al. 1993b).

4.5 SUMMARY

Table 4-2 presents a list of the various reconnaissance methods that can be used to characterize candidate areas of the Canadian Shield during the site screening stage. These methods would provide the geologic and hydrogeologic information necessary to assess the potential suitability of the area for locating a disposal vault. Integration of the characterization data from these information sources into maps and tables showing those factors that relate to disposal system performance and safety would enable a smaller number of potentially technically suitable candidate areas to be identified. This information would provide the technical basis for interaction with potential host communities in the development of non-technical exclusion criteria, selection criteria, and ranking factors for candidate areas and candidate sites. It would allow technical comparisons to be made between potentially-suitable candidate areas in discussions with potential host communities.

TABLE 4-2

CHARACTERIZATION METHODS USED DURING SITE SCREENING

Method	Type of Information	Use
1. Compilation and analysis of existing data and maps	- Geologic maps and reports	- Determine geologic setting, lithologic distributions and heterogeneity. - Identify large geologic structures such as faults or fracture zones.
	- Airborne geophysical surveys and reports	- Same as above.
	- Soils and surficial geology maps	- Overburden/outcrop distributions, overburden characteristics.
	- Surface water hydrology maps, hydrologic records and topographic maps	- Drainage boundaries, runoff and potential groundwater recharge/discharge areas, hydro-power potential.
	- Meteorologic data, such as rainfall, precipitation, evaporation	- Combined with above to quantify groundwater recharge/discharge.
	- Forestry, soils and vegetation inventories	- Surface environment assessment.
	- Wildlife surveys	- Surface environment assessmen.
	- Mineral exploration records and reports including borehole records	- Mineral resources, geologic setting, lithology, structural features, subsurface data from borehole records.

continued . . .

TABLE 4-2 (continued)

Method	Type of Information	Use
1. Compilation and analysis of existing data and maps (continued)	- Water resource surveys, including any water supply boreholes	- Generally shallow groundwater conditions including water supply capacity, perhaps groundwater chemistry.
	- Seismic monitoring records	- Historical seismicity of region, combined with regional geological information to determine risk of seismic hazard.
2. Airphoto and topographic map analysis	- Various scales of black and white and colour photographs thermal infra-red photographs, topographic maps	- Lithologic variations, rock outcrop distribution. - Lineament analysis to assess fracturing, faults and fracture zones. - Distribution patterns and habits of wildlife and biota. - Vegetation patterns for identifying lithologic variations, groundwater recharge/discharge conditions. - Local and regional topographic variations. - Surface water drainage patterns and boundaries. - Location of groundwater springs or seepages, or 'deer' or 'moose' licks.
3. Satellite imagery	- Landsat TM (bands 1-7) - SAR images from ERS-1	- Terrain analysis: drainage, vegetation, outcrop distribution.

continued . . .

TABLE 4-2 (continued)

Method	Type of Information	Use
3. Satellite imagery (continued)	- Panchromatic images from SPOT	- Lithologic variations. - Lineament analysis, faults, fracture zones.
4. Reconnaissance geophysical surveys	- Aeromagnetic surveys	- Shape, depth, boundaries of pluton and other lithologies. - linear anomalies caused by lithologic variations, faults or fracture zones.
	- Airborne EM and VLF-EM	- Lithologic variations. - Location of linear features such as faults and fracture zones. - Overburden distribution and thickness.
	- Airborne radiometric	- Boundaries of pluton.
	- Airborne and surface-based gravity	- Shape, depth, boundaries of pluton and surrounding rock units.
	- Reflection seismic profiles	- Large fracture zones and large subsurface variations in lithology.
5. Reconnaissance geological mapping	- Lithologic mapping at outcrops	- Verify and refine existing geologic data base.
	- Fracture mapping at outcrops	- Spatial data on fracture distribution, frequency, orientation and history.

continued . . .

TABLE 4-2 (concluded)

Method	Type of Information	Use
5. Reconnaissance geological mapping (continued)	- Fracture mapping at outcrops adjacent to potential structural features	- Determine location, extent, and orientation of major faults and fracture zones. - Establish any associations with lithologic variations.
	- Petrographic analysis of samples of major lithologic units and fracture infill minerals	- Develop tectonic history of pluton and its geologic structures.
6. Reconnaissance hydrologic/hydrogeologic surveys	- Drainage, runoff patterns, range of water level fluctuations	- Define drainage/watershed boundaries. - Range of volumes of surface water runoff.
	- Examine seepage and spring locations, rock outcrops, exposures of surficial deposits for permeability characteristics	- Initial assessment of groundwater movement, recharge/ discharge relationships.
7. Geochemical surveys	- Surface water chemistry	- Surface water runoff/groundwater discharge relationships.
	- Chemistry of springs and seepages	- Identify groundwater discharge/ flow system relationships.
	- Reconnaissance soil gas surveys	- Identify possible locations of discharge from deep groundwater flow systems.
	- Electrical conductance of of lake/river bottom sediments and bottom waters	- Locate discharge of groundwater.

5. IMPORTANT TECHNICAL FACTORS IN SITE EVALUATION

5.1 INTRODUCTION

Diffusion and advection, in groundwater within pores and cracks in the rock surrounding the underground disposal vault, are the most significant mechanisms by which contaminants could be transported to the surface from a deep disposal vault. In the disposal concept, slow groundwater movement in the plutonic rock surrounding the vault is expected to provide an effective barrier which will inhibit and delay the migration of contaminants from the vault. Potential disposal vault locations would be initially identified within the candidate areas using knowledge of the large scale groundwater flow conditions in the rocks of the candidate areas. Thorough knowledge and understanding of the groundwater flow and diffusion paths through the rocks would be required, to establish the relationship between pathways from the potential disposal vault location and the local and regional groundwater flow systems.

Site evaluation would involve surface and subsurface investigations to provide an understanding of the groundwater flow conditions both at the local scale for the site of the potential disposal vault location as well as at the larger size scale of the surrounding candidate area. The chemistry of the groundwater and the rock must be known because these control the rate of corrosion of containers in the vault and affect contaminant movement along the groundwater transport paths through the rock. The properties governing the thermal, mechanical and hydrogeological responses of the rock due to the construction and operation of the disposal facility must also be determined. These responses could alter the groundwater transport paths surrounding the disposal vault or they could change the transport properties within the transport paths.

Once the hydrogeological setting of the candidate area was known and the location, orientation and interconnections of large fracture zones had been established it would be particularly important to determine the distribution, size and solute transport properties of the less fractured intrablock regions of the rock between the fracture zones. Sparsely fractured, lithologically homogeneous intrablock regions at 500 m to 1000 m depth would be the favoured locations for the waste emplacement rooms of the disposal vault.

The characterization performed during site evaluation would be designed to provide the information necessary to develop this understanding of the candidate area, potential vault locations, and the candidate site. The focus would initially be on understanding the regional groundwater conditions, to identify potential vault locations within the candidate areas and it would narrow during the successive steps of site evaluation to determine the local conditions surrounding the rock volume that appears preferable for locating the disposal vault.

Contaminants from the vault that would eventually reach the surface environment would travel either through groundwater flow paths to natural groundwater discharge locations at surface or to the locations of water supply wells that draw water from the groundwater regime. In our analysis of the long term impacts of disposal we consider wells that are present now as well as those that may be drilled sometime in the future (Davison et al. 1994). Once contaminants reached the surface at these groundwater discharge locations, there would be a variety of pathways by which plants, animals and people could be exposed to harmful effects. Therefore, information would be needed from the site and its surroundings to determine how contaminants would move through surface sediments and soils, water bodies, the air and the food chain from the groundwater discharge locations (Davis et al. 1993).

Several geotechnical and environmental factors relate to the potential movement of waste contaminants by groundwater flow through plutonic rock to surface discharge areas. These factors, discussed more fully in the following sections, are as follows:

- pluton geometry, major lithologies and contacts, metamorphic and deuteric alteration,
- structural style, especially the fracturing, and the geometry and age of development or rejuvenation of the fractures,
- groundwater flow and solute transport,
- stress field,
- thermal field, and
- climate, infiltration, drainage, and biota.

5.2 PLUTON GEOMETRY, MAJOR LITHOLOGIES AND CONTACTS

The size and shape of a pluton, the major lithologies (rock types), their geometry, and the physical and chemical properties of the lithologies are important because they relate to the hydrogeologic properties of the rock that control contaminant transport. Furthermore, because the size and shape of the pluton are related to the homogeneity of characteristics such as mineral fabric, fracturing, and in situ stress conditions, they affect how the rock will respond to excavation and to the thermal and hydrogeological changes caused by a nuclear fuel waste disposal vault.

The shape and size of a pluton are partly governed by the age of the plutonic intrusion and its relationship to any subsequent orogenic activity. This tectonic age, and the metamorphic/tectonic environment into which the plutonic magma intruded before crystallizing, determine the original size and shape of the pluton, its rate of cooling, and its degree of subsequent deformation. Knowledge of the original shape, which is a clue to the mode of intrusion, and of the subsequent deformation can be used together with information about the relative level of the present erosion surface to assist in predicting the location and orientation of internal pluton structures such as fractures.

Some types of plutons tend to be larger than others. The larger the pluton the greater the likelihood that it contains larger volumes of rock with uniform physio-chemical conditions. Also if heterogeneities exist on a large size scale their exact locations and geometry may be more readily determined than if they exist on a small size scale. Pluton size affects the cooling, crystallization and deuteric alteration rates during and after intrusion which, in turn, determine how the intrusion fractured as it cooled and adjusted to the regional stress field. Both primary and secondary rock mass mineral fabrics and chemical zoning are often oriented relative to the geometry of the pluton. These fabrics also control the location of fractures that develop during later, brittle-deformation periods (Stone et al. 1989). Though the overall chemical composition and material properties of a pluton are largely controlled by the deep crustal tectonic regime in which the magma evolved, the chemical and mineral zoning of the pluton are related to the shape and size of the pluton.

A detailed knowledge of the pluton petrology, the genesis of the magma, its mode and environment of intrusion, its lithology (chemical and mineral composition and zonations), and its evolution over time through crystallization, deuteric alteration, magmatic dyking, and metamorphism, is extremely important in assessing the contaminant transport properties of the pluton. For instance, the original composition of the intrusive magma affects the nature of large-scale compositional zoning in the pluton and also partly determines the assemblage of minerals which comprise the rock. The mode of intrusion also partly controls large scale compositional layering. Studies of the Lac du Bonnet Batholith have shown, this strongly affects the location of subsequent faulting and fracturing (Everitt and Brown 1992). The depth of burial and the temperature at various stages of pluton evolution, together with cooling rates, affect the formation of large scale and small scale geologic structures, such as foliations, dykes and fractures in the plutons (Stone et al. 1989, Kamineni et al. 1990).

The crystallization of a magma is a lengthy process during which the pluton can be affected by changes in the regional environment such as the reduction in confining pressure by uplift. Our studies have shown there was about 5 km uplift between the initial, primary crystallization of the granitic Lac du Bonnet Batholith and the crystallization of late-stage, pegmatite-aplite dykes, (Brown et al. 1989a). Other internal changes can also occur in the pluton during such long periods of slow crystallization. For example, rock material from surrounding country rocks can be assimilated into the magmatic melt. As crystallization proceeds, immiscible hydrous and carbonic (as opposed to silica-rich) fluids may separate. This occurs in several gradual stages, or, in cases of retrograde boiling, the fluids may separate explosively to form hydrothermal fracture networks in the pluton. While the pluton remains hot these hydrothermal fluids react with minerals formed earlier. This process of partial recrystallization during and after the late stages of primary crystallization is known as deuteric alteration (Hyndman 1972). One change that often occurs during deuteric alteration is the alteration of biotite to chlorite, which releases iron that can impart a pink coloration to the rim zone of a granitic pluton.

Deuteric alteration and recrystallization, after there has been sufficient primary crystallization of the cooling magma to support a regional differential stress, have developed several of the foliation fabrics present in the Lac du Bonnet Batholith. These structures are important because mineral fabrics and microstructures can have an influence on the permeability of the sparsely fractured portions of the pluton (Kamineni and Katsube 1982, Katsube and Kamineni 1983) and can control the location of fractures that formed later in the rock (Stone et al. 1989).

Other physio-chemical properties such as thermal conductivity, strength and elasticity are functions of the lithologic composition. For example,at the Lac du Bonnet Batholith the altered "pink" granite is stronger in unconfined uniaxial compression than the unaltered "grey" granite (Annor and Jackson 1987).

The nature of the major lithologic contacts is important because the physical, chemical, and hydrogeological properties of the rocks separated by the contact may be significantly different. The contact itself may have different physical, chemical, or hydrogeological properties from the rocks on either side. This is because the contacts have been the loci of strong deformations and have been preferentially fractured during the geologic past. It will be important during site evaluation to determine if the contacts between rock units represent preferred groundwater pathways.

5.3 STRUCTURAL STYLE AND FRACTURING

Knowledge of the structural style of the candidate site and the surrounding area is required to relate the geologic structures seen at the site to the regional structure of the Canadian Shield. This is needed for evaluating the long term stability of the rocks at the site and for assessing the nature and extent of the variability in physical properties of the rocks.

A detailed knowledge of fracturing is needed because the pathways for movement of groundwater in the rock at the site will be controlled primarily by the distribution of fractures, joints and zones of intense fracturing (faults and fracture zones).

Fracture zones and faults constitute the major pathways for past and current groundwater movement within the plutonic rocks of the Shield. They are likely to be the most important potential future pathways for contaminant migration from a disposal vault located in a plutonic rock formation of the Shield. Information on the locations, dimensions, orientations and relative ages of the fractures at the site is required to reliably predict the fracture patterns within the blocks of rock which are bounded by the larger fault zones.

The locations, orientations, extents, interconnections and permeability characteristics of the larger fault zones of the site and its surroundings must be thoroughly known because these would be expected to be the dominant potential groundwater flow paths through the rock. The spatial arrangement of these fault zones relative to each other and relative to the topography of the land surface determines the nature of the groundwater flow systems that occur in plutonic rocks of the Shield.

The chemical composition of any minerals that occur in the fractures or faults must be determined. This provides information regarding the relative ages of the fractures. These minerals also strongly affect the degree to which chemical interactions would retard the transport of any contaminants moving through the rock in the groundwater (Vandergraaf 1982, Vandergraaf and Ticknor 1993).

Other important aspects of fracturing that must be examined are the properties and geological history of fractures that are presently closed or filled with minerals and the nature and geological history of any alteration that has occurred in the rock adjacent to faults and fractures. Filled or closed fractures could potentially be reopened by thermal, mechanical and hydraulic changes created by the construction or operation of the disposal vault or by other naturally-occurring future disruptive events or processes such as the onset of continental glaciation or isostatic rebound following glaciation or denudation.

Studies of the orientation, infilling mineralogy and reactivation history of open and filled fractures also help geologists to reconstruct the deformation history of the rock (Kamineni 1989). This aids in understanding the past and current state of in situ stress in the rock and can be used to predict how the fracture network is likely to respond to any future changes in the state of stress. This is used to predict the likely mechanical behaviour of the rock during future disruptions (Asmis 1984).

Alteration adjacent to faults and fractures causes significant changes to the physical, chemical and hydrogeological characteristics of the rock. Under low temperature conditions (<100°C), the alteration of crystalline rock is essentially characterized by the production of clay minerals and iron hydroxides which are both hydrated phases, (Kamineni and Gascoyne 1986, Gascoyne and Cramer 1987, Griffault et al. 1993, Kamineni et al. 1993b). The hydrated minerals may develop by alteration of primary plagioclase which is characterized by high alteration kinetics (Kamineni et al. 1993a) or by alteration of ferromagnesian minerals. The hydrated minerals may also be found as alteration products of high temperature hydrothermal fracture fillings in cases where there has been a reactivation of early fractures (Kamineni 1986, Kamineni and Gascoyne 1986, Griffault et al. 1993).

Rock alteration may affect the pore structure of the rock either by reducing the interconnected porosity due to crystallization of secondary phases within the pore spaces or by increasing the porosity by dissolving and enlarging existing pores or creating new ones (Katsube and Kamineni 1983). The accessibility of fluids to affect alteration may vary during the various alteration processes which may induce variable degrees of alteration adjacent to the fractures, (i.e., control the amount of plagioclase and ferromagnesian minerals that are affected).

Weathering processes and reactivation of previously-formed fractures may affect the original distribution of the natural radionuclides, U and Th and rare earth elements (REE) adjacent to the fractures. For example, relatively recent migration of naturally-occurring radionuclides in the U-decay series has been observed in the alteration halos around permeable fracture zones to depth as great as 1000 m in the granitic Lac du Bonnet Batholith (Griffault et al. 1993, Gascoyne and Cramer 1987).

The distribution patterns of natural U, Th and rare earth elements (REE) may vary significantly, on a scale of centimetres to metres, with the degree of alteration and the mineralogy of fracture fillings (Kamineni et al. 1986). Fracture fillings may have high concentrations of U and REE (Kamineni 1986, Kamineni et al. 1986, Griffault et al. 1993) due to both sorption on specific mineral phases (Ticknor, et al. 1989, Kamineni et al. 1983) and precipitation of U- and/or REE-bearing phases (Kamineni and Bonardi 1983). Studies of these elements can provide information on the mobility and retention of natural radionuclides in fracture margins, including the overall distribution of these elements. It can also provide information regarding their retention in the alteration sites, retention in the nearby fractures, retention in more distant fractures and retention on pre-existing mineral phases during reactivation of early fractures. Radiometric dating techniques can be used to determine the timing of various fracture reactivation events. These in turn provide useful analog information on many processes that could affect the potential mobilization/retention within fractures and fracture zones of radionuclides that could be released into the fractures in the rock from a nuclear fuel waste disposal vault.

5.4 GROUNDWATER FLOW, GROUNDWATER CHEMISTRY AND SOLUTE TRANSPORT

Thorough knowledge of the groundwater conditions within the rocks and overlying unconsolidated sediments at the disposal site and in the surrounding area is needed along with knowledge of the properties of the groundwater transport pathways from vault depths to surface. This knowledge is used to develop and calibrate mathematical models which simulate the long term movement of contaminants from a disposal vault through groundwater pathways in the surrounding rock to groundwater discharge locations at the surface. We refer to the rock surrounding the disposal vault and the overlying sediments as the geosphere so we have called these models geosphere models. The development and application of geosphere models for performance assessment calculations are discussed in the report by Davison et al. (1994). Geosphere models rely heavily on site specific geotechnical information, particularly the regional and local scale subsurface hydrogeologic information that is obtained during site evaluation.

A variety of physical properties of the groundwater conditions at the site and in the surrounding area must be determined to establish the rate at which groundwater movement occurs through the rock and to establish the various flow paths or flow systems along which the groundwater movement takes place (Davison et al. 1994). These properties include:

- the hydraulic conductivity or permeability of the rock, its fracture systems, and overlying sediments,
- the porosity (and in particular the interconnected porosity) of the rocks and sediments,
- the spatial and temporal distributions of groundwater pressures, the degree to which solutes mix, spread or otherwise disperse as they are transported in the groundwater flow systems, and
- the compressibility of the groundwater and the rock matrix/fracture network.

In order to assess the impacts of constructing and operating a disposal vault, there must be a good understanding of how these properties vary spatially at the site of the disposal vault and in the surrounding area. There must also be a good understanding of how these properties might change either as a result of the changes in thermal and stress conditions that are created by the construction and operation of the disposal vault or naturally in response to long term climatic trends or disruptions (Davison et al. 1994).

A thorough knowledge of the chemistry of the groundwater can help to define the groundwater flow patterns at the site and surrounding area. This information can assist in determining the current rates of groundwater movement and the origin of the natural solutes in the groundwater (Bottomley et al. 1990, Gascoyne and Kamineni 1993, Gascoyne and Chan 1992). The groundwater chemistry also comprises a significant part of the natural geochemical environment within which the waste form and engineered components of the vault would be placed and it would affect the rate of radionuclide release from the waste form by corrosion (Johnson et al. 1994a). It will also affect the rate of radionuclide migration through the buffer and backfill materials placed around the wastes in the vault (Johnson et al. 1994a). Furthermore, knowledge of the chemistry of the groundwater within the groundwater flow paths in the rock would be combined with the knowledge of the minerals lining the flow paths to estimate the chemical sorption properties along the flow paths (Vandergraaf and Ticknor 1993).

In addition to understanding the physical and chemical aspects of the groundwater flow systems at and surrounding the site, we need to determine how different solutes can move through groundwater in those sparsely fractured regions of the rock of very low permeability by the process of diffusion (Davison et al. 1994). Diffusion causes a solute to slowly spread away from a location by molecular motion only, without any flow of the groundwater.

5.5 STRESS FIELD

The nature and time dependent rate of the responses of the surrounding rock mass and groundwater systems to the construction, operation and closure of the disposal vault are controlled by the stress field, the rock properties, the excavation method and the excavation geometry. A thorough understanding of the in situ stress field is required for designing the underground tunnel and room layouts, the geometry of excavated openings, and the engineered structural supports (Simmons and Baumgartner 1994). This understanding is also required to assess the long-term stability of the rock surrounding the disposal vault during the occurrence of potentially disruptive events such as glaciation (Davison et al. 1994).

Knowledge of the stress field in the rocks at the site can also be used to understand the permeability distributions which occur within any fractures and fracture zones that are present. For instance our studies at the URL show that the permeability patterns within the major fracture zones can be related to the surrounding stress patterns (Martin et al. 1990). Similarly changes in the state of stress can lead to changes in the permeability of fractures so stress/permeability relationships need to be understood (Gale et al. 1990, FRACFLOW Consultants Inc. and NGI 1993). This is particularly important to determine the effects of excavation- and thermal-induced stress changes on the permeability of the rock near the vault.

The in situ stress state comprises the effective lithostatic load, active tectonic stress and remnant stress. At both the near-field (1-1000 m) and intermediate- (1-10 km) size scales the stress field in the rock can be heterogeneous both in magnitude and orientation, and strongly affected by nearby faults and lithostructural fabric. This has been shown by recent detailed studies in the Lac du Bonnet Batholith at the WRA, (Brown et al. 1988, Brown et al. 1989b, Martin 1990, Martin and Chandler 1993, Martin et al. 1990) and has also been shown by other, less detailed studies of the Shield in Western Ontario, (Herget 1980, Herget and Arjang 1990). In comparison, the stress field at the large size scale of the tectonic provinces of the Shield can be considered relatively homogeneous (Zoback and Zoback 1981, Adams 1987). This large scale stress pattern is of interest during initial site screening (as a factor related to Shield stability) whereas during site evaluation, knowledge of the smaller scale patterns and variations is required.

An interpretation of the orientations of paleostress fields can be drawn from mapping the orientation and age of structural elements within the pluton and in the surrounding rocks. This type of analysis leads to a better prediction of how structures such as fractures and fracture zones vary in space and also may identify orientations where these structures should be expected. Brown et al. (1988) give an example of such an analysis at the Whiteshell Research Area. Although this type of work would be initiated early in site evaluation when surface mapping and borehole drilling are being done, most of the understanding would be developed when actual underground measurements of the in situ stress conditions are available from exploratory shafts and tunnels.

5.6 THERMAL FIELD

Knowledge of the thermal field at the site and the properties that control it is important for the engineering design of the disposal vault. The temperatures that develop in the waste container, the buffer, and in the rock near the vault depend upon the initial temperature distribution in the rock (geothermal gradient) and the groundwater, the distribution of the heat-generating waste in the disposal vault (which raises the temperature in the rock), and the thermal properties of the rock surrounding the disposal vault.

The thermal field can be slightly disturbed during site characterization by borehole drilling. Therefore studies of the groundwater temperatures in boreholes can also help to identify the location of permeable fractures in the boreholes (Drury and Lewis 1981, Drury 1984a,b, Drury and Taylor 1987).

5.7 CLIMATE, INFILTRATION, DRAINAGE AND BIOTA

Some of the water which falls as precipitation infiltrates the subsurface and recharges the groundwater flow systems in the rocks and sediments. A knowledge of the amount and the temporal and spatial distribution of precipitation runoff and infiltration in the region surrounding the disposal site would be needed to construct a reliable model of the groundwater flow conditions (Davison et al. 1994).

Generally the groundwater table within the Canadian Shield is very close to ground surface and is a subdued replica of the topography. In low lying areas the water table is less than 1 metre below ground surface. These low lying areas are often discharge areas for local, intermediate, or regional groundwater flow systems. Areas of higher topographic elevation have a correspondingly higher water table than adjacent low lying areas. The groundwater level is generally from 1 to 10 metres below ground surface in upland areas (Thorne 1990b). On the Shield the topographic highs often occur as either bedrock outcrops or bedrock highs which may be covered with a thin veneer of overburden. Infiltration and percolation of rain and snowmelt restores moisture to the unsaturated soil moisture zone and recharges the groundwater flow systems in the rock from these topographic highs (Thorne and Gascoyne 1993).

The water table most often reaches maximum levels subsequent to the spring snowmelt, especially if spring rains supplement the moisture from snowmelt. Minimum water table elevations occur in late winter, just prior to snowmelt. Water levels also decline during the summer period in response to moisture loss to evapotranspiration. Most precipitation during the summer period is used to meet vegetation demands and reduce the soil moisture deficit of the unsaturated zone. During the warm periods of the summer little if any moisture is available for groundwater recharge except following intense rainfall events (Thorne 1990a, 1990b, Thorne 1992, Thorne and Gascoyne 1993).

Regardless of the amount of precipitation that occurs during the spring or autumn the water table in rocks of the Shield generally rises to about the same level every year. This indicates that the rock mass is always very near its limit of saturation and only requires a small amount of infiltration each year to reach this limit. After full saturation is attained, any additional water added as precipitation does not infiltrate to the groundwater regime, but runs off as surface stream flow. Only about 1 to 2% of the total annual precipitation is required to replenish the water that discharges to surface from groundwater flow systems in the rocks of the Shield.

In most regions of the Shield the annual range of natural water table fluctuation would be expected to be small in comparison to either local or regional topographic relief. However it will be necessary to establish the range of fluctuations that occur in the vicinity of potential disposal site locations. Other aspects of examining the patterns of drainage, soils, vegetation, wildlife and biota during site evaluation would be very similar to those already discussed for site screening in section 3.7 and chapter 4.

5.8 THE APPROACH TO SITE EVALUATION

Site evaluation will include:

- thorough surface and subsurface characterization studies of the rocks, soils and biota at candidate areas, potential disposal vault locations and candidate disposal sites,
- disposal facility design studies, and
- environmental and safety assessments of alternative disposal vault locations, the preferred candidate disposal site, and alternative facility designs.

The objective of site evaluation is first to identify alternative locations of potentially suitable disposal sites in the candidate areas and then to narrow down the alternatives to select a preferred candidate location for the disposal vault.

Site evaluation involves the use of field and laboratory investigations to obtain the knowledge and understanding of the important geotechnical and environmental conditions of the site and its surroundings as listed in Section 5.1. Site evaluation also includes how this information is used to assess the safety of any particular location in the candidate area for the potential disposal of nuclear fuel wastes (Davison et al. 1994, Goodwin et al. 1994). It comprises all the geotechnical and environmental investigations needed to: 1) locate and design the disposal vault taking into account regional and site specific geologic, hydrogeologic and surface environment attributes, 2) assess the environmental impacts of alternative vault locations and facility designs, and 3) assess their long-term safety of these alternatives.

Similar to site screening, the full scope of site evaluation and the determination of any particular site selection or rejection criteria should be decided during the development of the siting process. These should be decided in consultation with the potential host communities, government and regulatory agencies to allow for appropriate integration of natural and human environment factors and engineering design factors (AECL, 1994a).

However, unlike site screening which would largely involve an office compilation of existing information with only minor reconnaissance field investigations, site evaluation would mainly involve careful field investigations of the surface and subsurface conditions of the potentially-suitable candidate areas and sites and their surroundings to obtain new information on these conditions.

During site evaluation, characterization activities would focus on examining progressively smaller geographic areas. The site evaluation work would be conducted at various size scales. These size scales would range from initial large scale investigations of potentially-suitable candidate areas of at least several hundreds of square kilometres in size (nominally about 400 km^2) which were selected during site screening, through the disposal site scale (about 25 km^2) to the local vault scale (about 4 km^2) where the investigations would focus on determining conditions in the particular volumes of rock that appear suitable for the waste emplacement rooms. Figure 5.1 illustrates the various geographic size scales that the characterization activities must address during site evaluation.

The characterization performed during site evaluation will progress through several successive steps:

- regional reconnaissance investigations;
- thorough regional surface and subsurface investigations, including boreholes drilled at grid areas distributed throughout the candidate areas and possibly outside the candidate areas to establish the regional hydrogeologic setting;
- surface and subsurface investigations of the potentially suitable candidate disposal sites including borehole drilling, geophysical, geomechanical and hydrogeological investigations for positioning the exploratory shafts and tunnels at the preferred candidate vault site; and

- underground investigations in the exploratory shafts and tunnels at the candidate vault site to confirm the site conditions and to assist in locating the actual underground waste emplacement areas.

Site characterization activities would not end when the waste emplacement areas have been identified. Rather, site characterization would continue throughout all the subsequent major sequential stages of the waste disposal project (Construction, Operation, Extended Monitoring, Decommissioning and Closure). This report mainly discusses the characterization activities that would need to be performed during the siting stage of the project. These involve: surface-based methods, methods performed in boreholes drilled from the ground surface to investigate the subsurface conditions, and the underground methods performed in exploratory shafts and tunnels at the candidate site. A report by Everitt et al. (1994) describes the characterization activities that would be conducted underground during the subsequent stages of the project.

5.8.1 Regional Reconnaissance Studies During Site Evaluation

Regional reconnaissance airborne and surface-based investigations would be conducted over the entire region surrounding the candidate area before any boreholes are drilled. Because a large amount of reconnaissance information will have already been obtained during the preceding site screening phase, this period would be of relatively short duration in the overall schedule for site evaluation, possibly lasting three years. There would however, be considerable overlap of the reconnaissance investigations with subsequent site evaluation investigations.

The objective of the reconnaissance investigations during site evaluation is to begin to establish an understanding of the main lithologic and structural features of the regional area covering several hundreds of square kilometres in size surrounding the candidate area. This information would be used to select the locations of smaller study areas (we refer to these as grid areas) of about 1 to 4 km^2 area in size where detailed surface investigations and subsurface investigations in boreholes would be conducted. These grid area studies would provide detailed information at a few key locations to develop the large scale understanding of the geological, geomechanical and hydrogeological conditions of the candidate area.

We have developed and applied this approach of using a patchwork of small grid areas in characterizing the geologic and hydrogeologic conditions of three geologic research areas at East Bull Lake, Atikokan and Whiteshell. At East Bull Lake two grid areas were examined; three grid areas were studied at Atikokan; and seven grid areas were studied at the Whiteshell Research Area. Figures 5.2, 5.3 and 5.4 show the locations of these grid areas and how they relate to some of the main geologic and hydrogeologic features in the research areas.

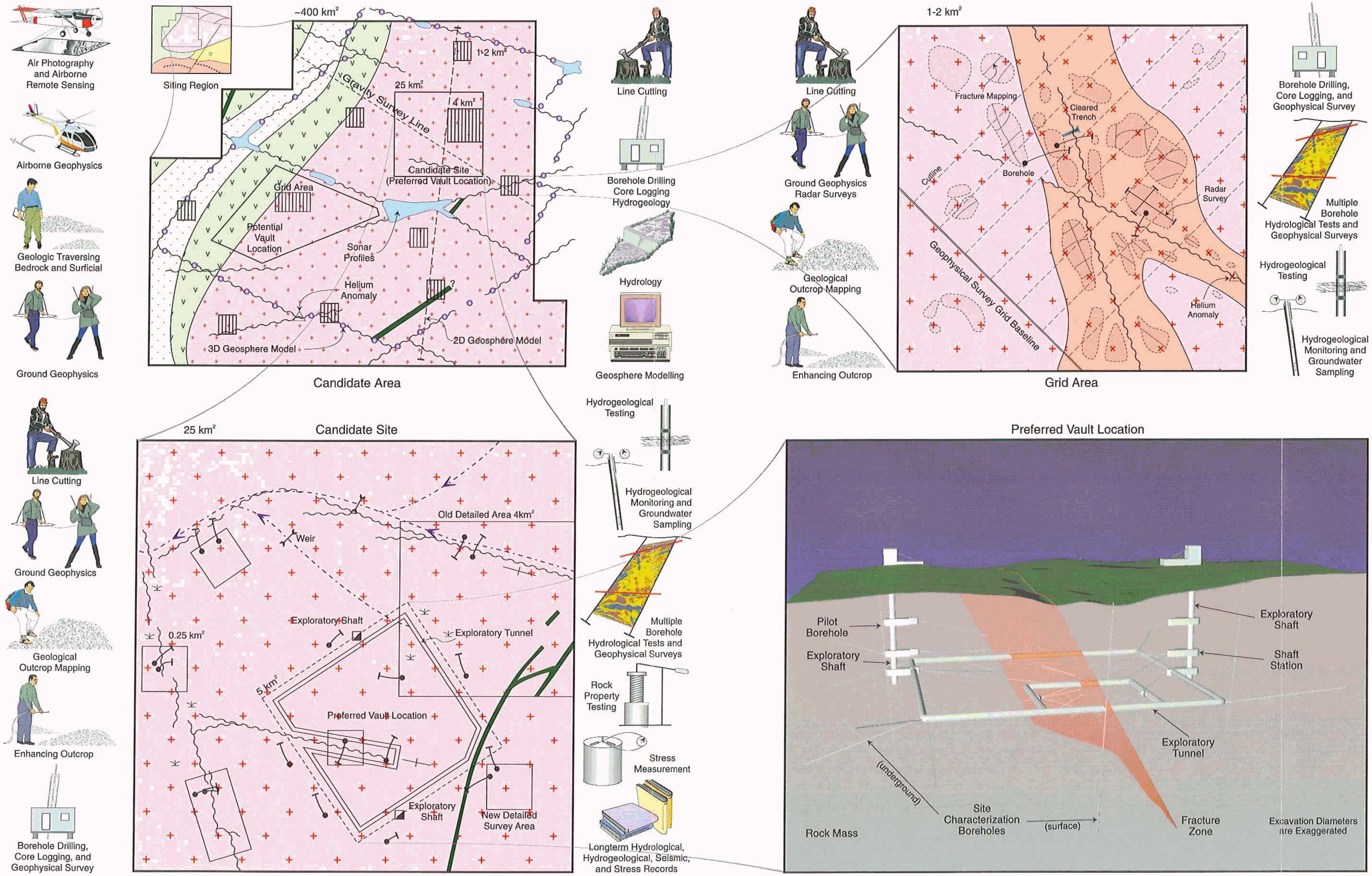


FIGURE 5-1: Schematic of Site Evaluation Process

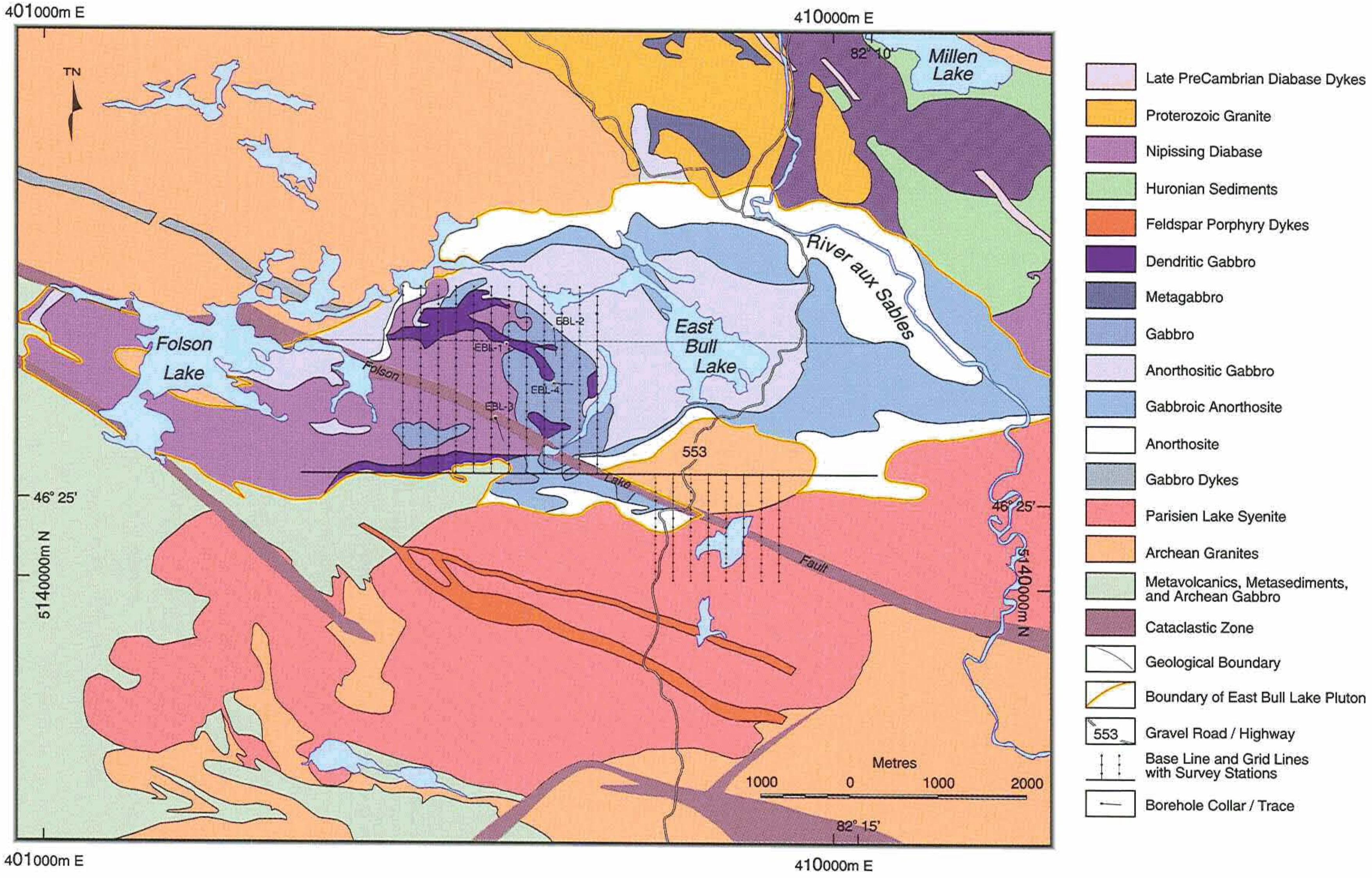


FIGURE 5-2: Location of Grid Areas and Local Geology at the East Bull Lake Research Area

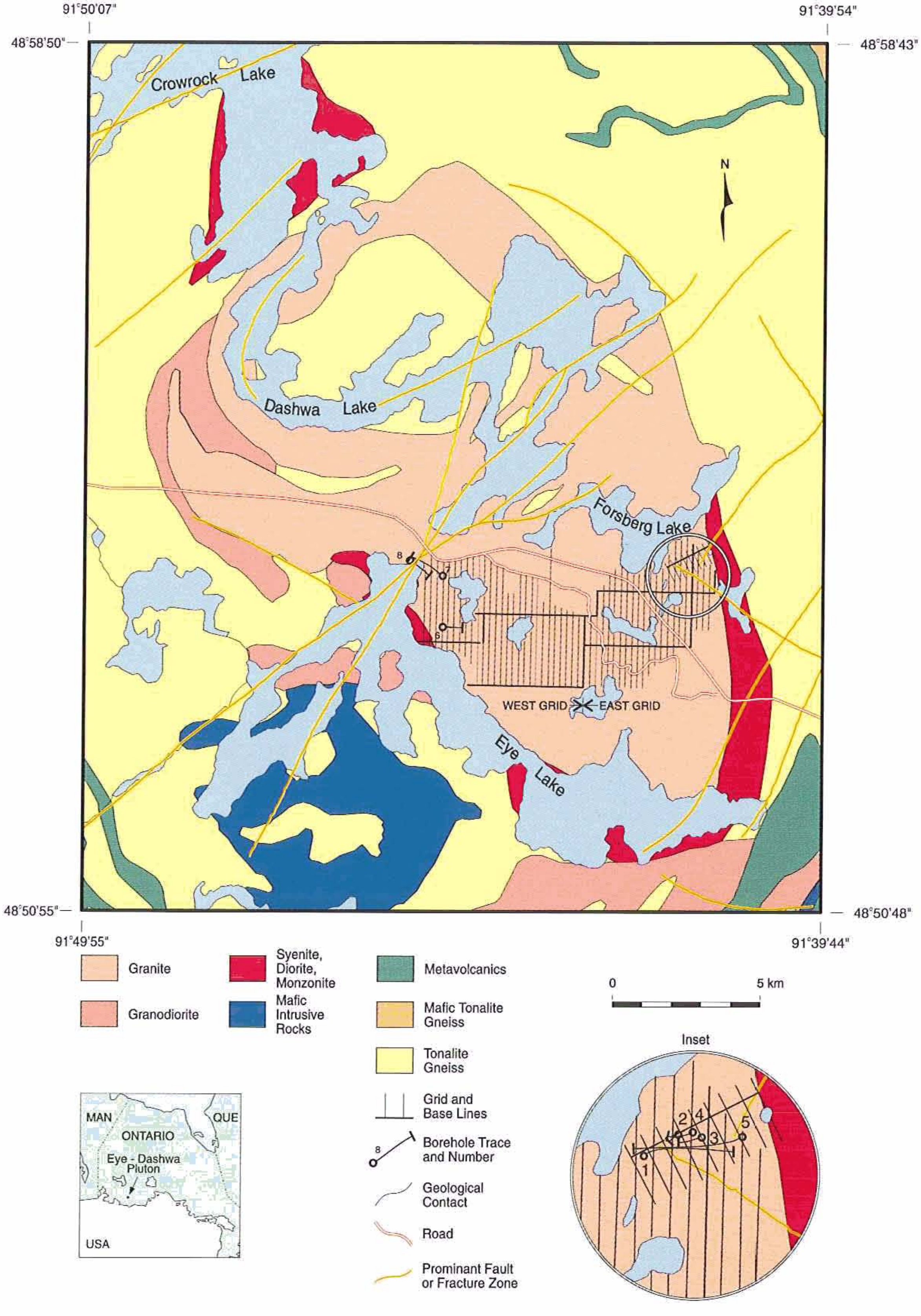


FIGURE 5-3: Location of Grid Areas and Local Geology at the Atikokan Research Area

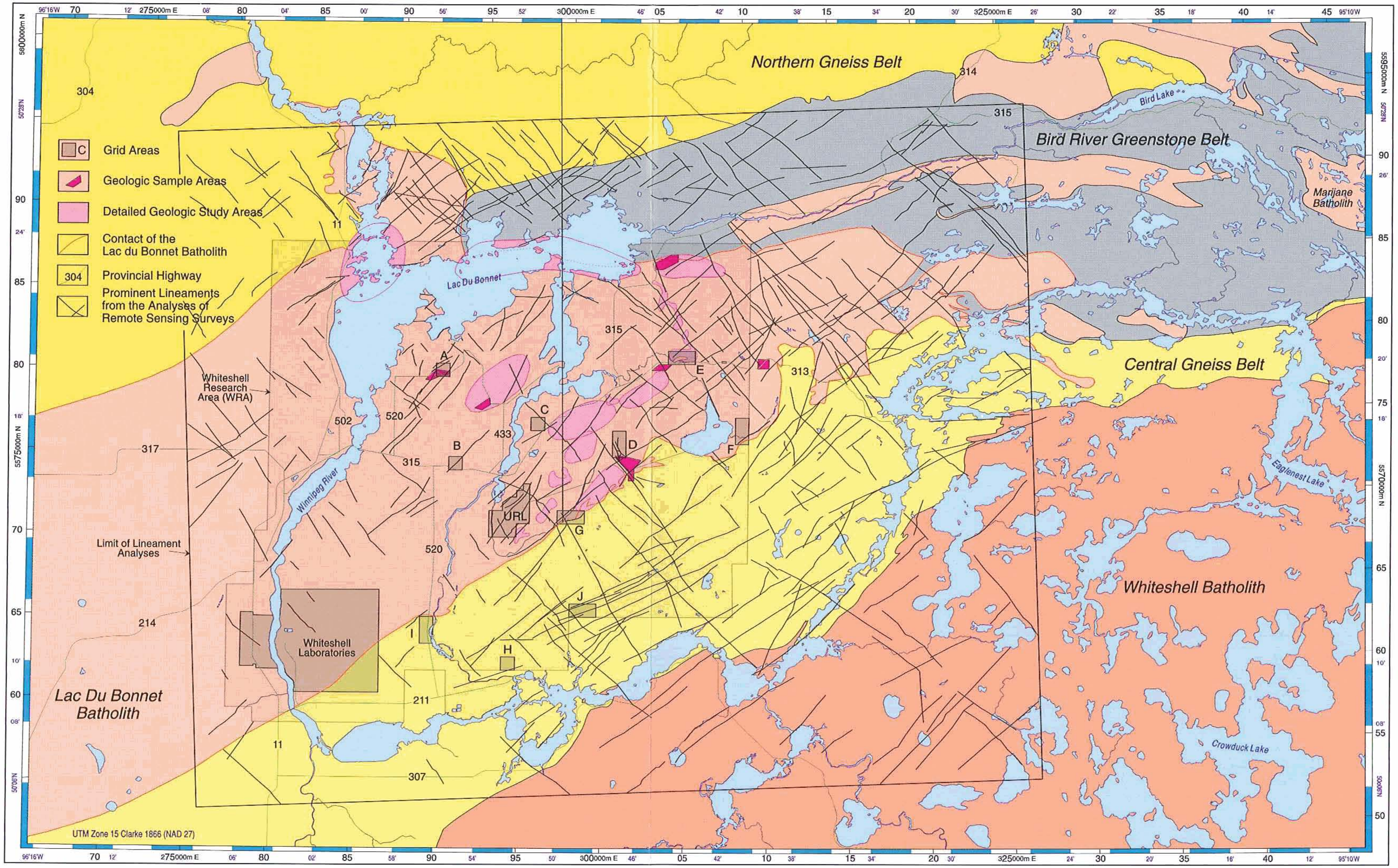


FIGURE 5-4: Location of Grid, Sample, and Detailed Study Areas Shown with Simplified Geology at the Whiteshell Research Area

5.8.2 Regional Evaluation Using Grid Areas

After work commenced on the grid areas, there would be a period of intensive surface and subsurface study in the candidate area when subsurface information would be obtained by conducting investigations in boreholes drilled from ground surface at the grid area locations. This period would likely take from five to eight years to complete. Many of the reconnaissance investigations which were begun at the start of site evaluation would be continued throughout this period.

Information from the large regional reconnaissance surveys and the smaller grid area studies would be combined to develop and calibrate a regional scale model of the groundwater flow and solute transport conditions of the candidate area and its surroundings. Sensitivity analysis with the model would assist in identifying where additional site evaluation studies might need to be conducted and where additional grid areas or boreholes might be required to improve the understanding. Once calibrated, this large scale groundwater flow model would be used in a performance assessment to help assess the potential environmental and safety impacts of placing a disposal vault at alternative locations in the area. Such an analysis would assist in determining a suitable location for the candidate disposal site. The complete performance assessment approach is described in AECL (1994a,b). The approach to postclosure safety assessment is described in Goodwin et al. (1994).

5.8.3 Characterization of Candidate Site for Disposal Vault

After a potentially suitable location for the disposal vault has been identified in the candidate area, most of the subsequent characterization work during site evaluation would focus on carefully determining the features and properties within and immediately surrounding the candidate site for the disposal vault. This would involve surface and subsurface investigations very similar to those done at the grid areas but at a considerably greater density than for the regional studies of the candidate area. This information would be used to construct a more detailed model of the geologic and hydrogeologic conditions of the disposal site (Davison et al. 1994). This model would assist in developing and assessing alternative conceptual designs of a disposal vault at the location and be used to conduct refined performance and safety assessment calculations of the alternative facility designs taking account of this thorough knowledge of the site conditions. The model would also be used to determine where additional site characterization information should be obtained for vault design purposes or to investigate particular features that could constrain waste emplacement activities. Also more information may be needed to calibrate and verify the groundwater flow and solute transport models or to reduce the uncertainty in the understanding of key site characteristics. There will also be a need to thoroughly investigate any other particular features of the site identified as siting constraints in the safety and performance assessments (Davison et al. 1994). Some of the information needed to select the locations for exploratory shafts and exploratory tunnels would also be collected at this time.

5.8.4 Underground Characterization in Exploratory Shafts and Tunnels

The final step in site evaluation would involve the underground characterization activities performed in exploratory shafts and tunnels at the preferred candidate vault site. This underground characterization would provide information to test and verify previous predictions of the expected underground conditions. These would include predictions of the hydrogeologic and geomechanical disturbances caused by the exploratory excavations. The underground characterization would also provide additional geotechnical information needed to complete the engineering designs of the disposal vault.

It is expected that the siting stage would end with the completion of the site characterization from the exploratory excavations and an application by the implementing organization for regulatory approval to proceed with the construction of an operating disposal facility at the candidate site.

The remainder of this report discusses the site evaluation technology developed in the CNFWMP since 1975 to determine the geologic, hydrogeologic, geochemical and geomechanical characteristics of plutonic rocks of the Canadian Shield. Chapter 6 describes methods for the initial evaluation of candidate areas. This involves the use of a patchwork of small grid areas where thorough investigations are conducted at surface and in the subsurface using deep boreholes. Chapter 7 describes methods for evaluating the conditions at the smaller geographic size scale of the candidate site for disposal vault. Chapter 8 describes the methods for underground characterization in the exploratory shafts and tunnels of a vault. Examples drawn from studies conducted at the various geologic research areas on the Shield are used to illustrate the application of the site evaluation methods at these scales.

6. SITE EVALUATION METHODS FOR LARGE GEOGRAPHIC AREAS OF THE SHIELD

6.1 RECONNAISSANCE-SCALE SITE EVALUATION METHODS

6.1.1 Introduction

The initial objective of reconnaissance-scale investigations during site evaluation would be to confirm that the relatively large, potentially suitable candidate areas selected during site screening have characteristics that are suitable for a disposal vault, making it worth the increased commitment of resources for subsequent characterization. Having done that, the next objective of the reconnaissance investigations would be to identify the geologic and hydrogeologic features of the candidate area that should be the focus of more detailed investigations using a patchwork of smaller grid areas. Thorough surface studies and subsurface studies in boreholes would be carried out on these grid areas. The grid area studies would either continue to confirm the potential suitability of the candidate area for locating a disposal vault or they would suggest that the area contained no suitable location so investigations could be abandoned at an early stage without further commitment of resources.

As in the reconnaissance investigations for site screening, the initial reconnaissance investigations which would be conducted on the candidate area during site evaluation, would employ traditional methods of field geology, mineral exploration, terrain analysis, and environmental analysis, many of which have been described previously in Section 4.3. However, more detailed surface investigations would be conducted during the regional reconnaissance studies for site evaluation than during site screening. These surface investigations would include the following:

- systematic geologic mapping and sampling of lithology and structural fabric elements in outcrop;
- 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;
- sonar reflection surveys of the bottoms of lakes or rivers to trace structural discontinuities beneath the water bodies which are evident on adjacent land and to examine the stratigraphy of the sediments deposited in the bottom of these water bodies 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 flora and fauna to help evaluate the sensitivity of the natural environment and to help identify groundwater discharge locations;
- 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 atmospheric meteorological, hydrological, floral, and faunal observations to establish baseline environmental conditions in the candidate area (Davis et al. 1993).

In many cases the reconnaissance work during site evaluation may require constructing access roads for transporting equipment and personnel and cutting grids of survey lines for geophysical and geological surveys. Unlike field investigations during site screening, which would involve only brief visits of a few days or weeks, the reconnaissance field investigations during site evaluation would be extensive and would span several years.

The regional reconnaissance investigations would yield two particularly important types of information for planning the subsequent phases of site evaluation, that involve subsurface investigations. First is the identification of features that may represent the surface expression of major groundwater flow pathways in the rock and soils. 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. Second is the identification of other small-scale heterogeneities in the rock. These include lithologic layering, textural or structural fabric, foliations, fracturing and jointing, and stress fields that indicate the possibility that the properties of the rock controlling groundwater flow and geomechanical responses may vary with direction (anisotropy). For example information from the mapping of fracture patterns in rock outcrops might reveal that the rock is likely to be more permeable in one direction than in another.

Some reconnaissance site evaluation methods have been applied at all of the geologic Research Areas on the Canadian Shield. Early studies at the Chalk River Research Area during 1977 to 1980 involved the development and use of many reconnaissance site evaluation methods (Thomas and Dixon 1989), but the most extensive studies have been performed at the East Bull Lake (McCrank et al. 1994b), Atikokan (Stone et al. 1992) and Whiteshell (Brown et al. 1994) Research Areas. The following sections present a number of examples of the use of reconnaissance scale site evaluation methods drawn from the work at these three research areas.

6.1.2 Regional Geological Mapping

Geologic mapping would be carried out over a large area of the country rocks surrounding a pluton to ensure that sufficient information would be obtained to determine the regional geologic and hydrogeologic setting of the pluton. Mapping ratios of from 1:5 for large plutons to 1:10 for smaller intrusions would be considered sufficient to establish this. For instance the geologic map produced for the Atikokan Research Area covers 1120 km^2 surrounding the 80 km^2 Eye-Dashwa Lakes pluton (Stone et al. 1992). At the Whiteshell Research Area reconnaissance scale geological mapping covered an area of 3500 km^2 surrounding the 550 km^2 exposed area of the Lac du Bonnet Batholith.

The types of geologic data that would be recorded during the regional mapping done at the reconnaissance scale are summarized in Table 6-1. From the traverses used to map the country rock surrounding the pluton, rock types, the percentage of dyking, and the degree of metasomatic granitization would be noted; obvious foliations of different types would be measured; the density of fracturing would be estimated; and oriented specimens would be taken for mineralogical, chemical, fabric and age dating studies.

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 1988a). Any kinematic evidence and unusual fracture infillings would be especially noted. Crosscutting relations would be examined to establish the relative chronology of lithology, fabric and structural features. Obvious fold data would also be measured.

The mapping done on rock outcrops in the pluton would involve the collection of similar data but would be considerably more detailed than that done on the rock outcrops outside of the pluton. Line samples of outcrops would be used to map fracture intensity. Fracture characteristics such as length, aperture and infillings would be recorded at these outcrops. The mineralogies of various intrusive phases of the pluton would also be estimated and many rock samples would be taken from the outcrops for laboratory analyses of lithology, mineralogy, fracture infillings and fabric.

6.1.3 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 pluton and to establish the history of any subsequent ductile and brittle deformations that may have occurred.

The laboratory samples would be examined for deformation evidence, such as foliation fabrics and fracture kinematic features. This can be very useful in establishing if the primary fabric of the rock had any control in the later development of fault or fracture zones (Stone et al. 1989).

Feldspar geothermometry can also be used to study the relative ages of fault zone formation (Kerrich and Kamineni 1988). Trace element analysis provides information for developing petrogenetic models. In particular, studies of the distribution of natural U, Th, and rare-earth elements in the rock and fracture filling minerals can provide insight into processes that affect radionuclide migration or retention in the rock. For instance, laboratory examination of rock samples from both the Lac du Bonnet batholith and the Eye-Dashwa Lakes pluton show that these elements were mobilized during periods of rock alteration early in the emplacement history of the plutons. However, these elements became reconcentrated in some fault zones through selective sorption and precipitation as minerals such as uraninite, bastnaesite, thorite and thorogummite (Kamineni 1986). Radiogenic isotope studies can also be useful in establishing the age of pluton formation and the subsequent ages of fracturing, faulting and associated alteration events (Peterman and Kamineni 1990).

6.1.4 Examples of Multidisciplinary Reconnaissance Site Evaluation

Multidisciplinary reconnaissance-scale site evaluation investigations were conducted at East Bull Lake Research Area from 1980 to 1982. The initial work (1980 and 1981) included a review of existing geological, hydrological and geochemical information, geological inspection of rock outcrops (Brown and Kamineni 1981, McCrank et al. 1983, Brown and Kamineni 1989), terrain analysis (Leech and Cooper 1982), and a variety of airborne and land-based geophysical surveys (Niblett et al. 1985) to establish the regional setting of a small gabbroic pluton (23 km^2). The pluton coincided with a well-defined positive anomaly in the gravity survey data (the gabbro has a higher density than the neighboring granitic rocks). Modelling of this data suggested that the pluton was only 500 m to 700 m thick. However, interpretation of the geological data collected by mapping exposed outcrops suggested that the pluton was conical-shaped with a maximum depth of about 900 m (Brown and Kamineni 1989). Geologic mapping, geophysical surveys and inspection of air photos revealed that two major regional faults cut through the margins of the pluton and there was strong compositional layering in the pluton with large lithological variation between layers.

More detailed regional geological mapping at the East Bull Lake Research Area during 1982 showed the pluton could be divided into seven lithological and textural units. This geologic mapping also showed there were numerous vertical dykes cutting through the pluton and these had a predominant alignment in a northwesterly direction (Brown and Kamineni 1989, McCrank et al. 1985). Airphotographs and topographic maps were used to generate a lineament map of the area, showing features that were likely to be significant faults and fractures or lithologic discontinuities (Kamineni et al. 1992). Figures 6.1, 6.2, 6.3 and 6.4, respectively show the regional geological map of the East Bull Lake pluton, the lineament map derived from airphotograph and topographic map inspection, the gravity map for the area, and the lineaments which are evident from VLF-EM survey data. This reconnaissance work was used to select an area of about 12 km^2 for more detailed surface investigation.

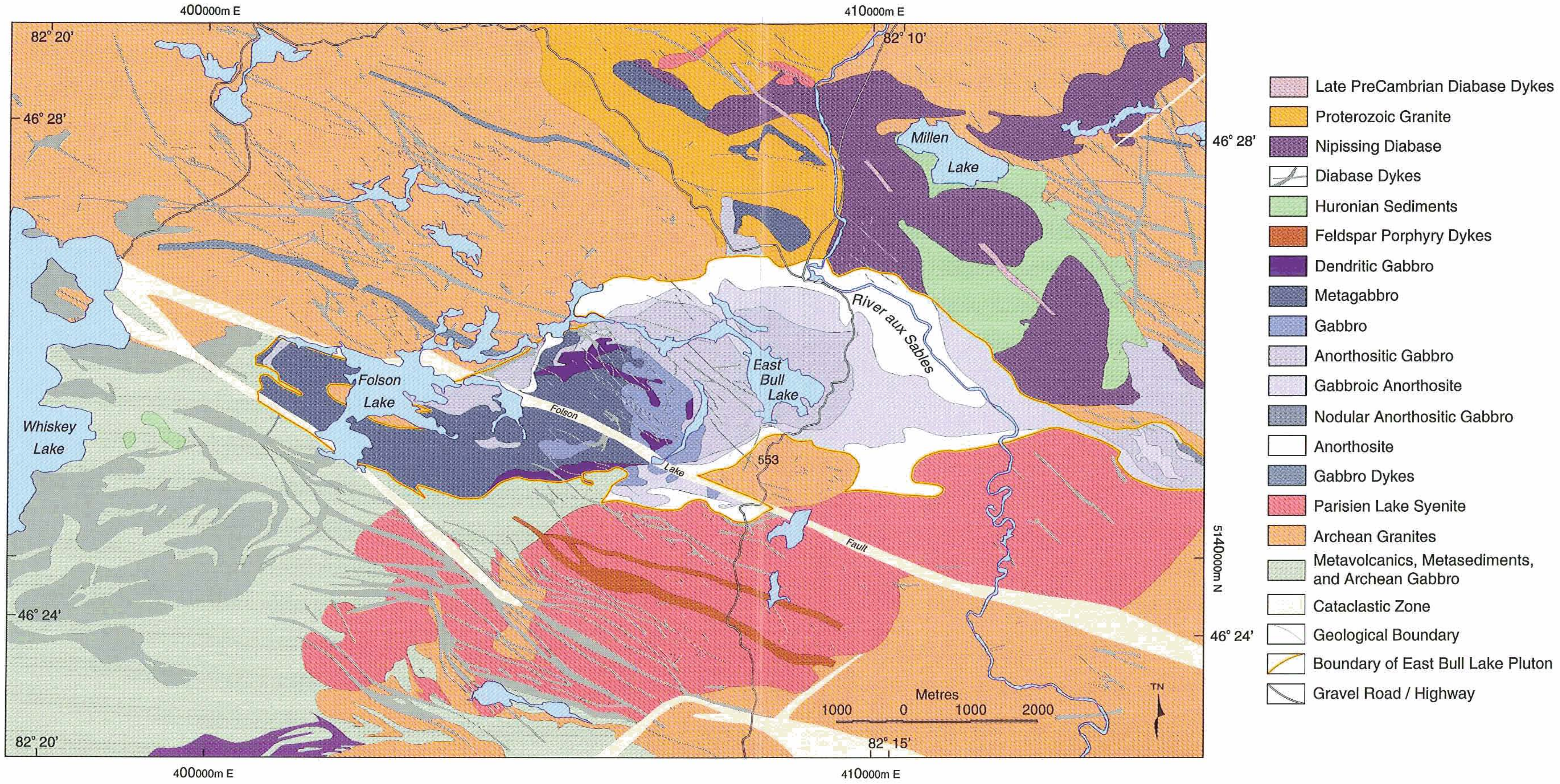


FIGURE 6-1: Regional Geology of the East Bull Lake Pluton

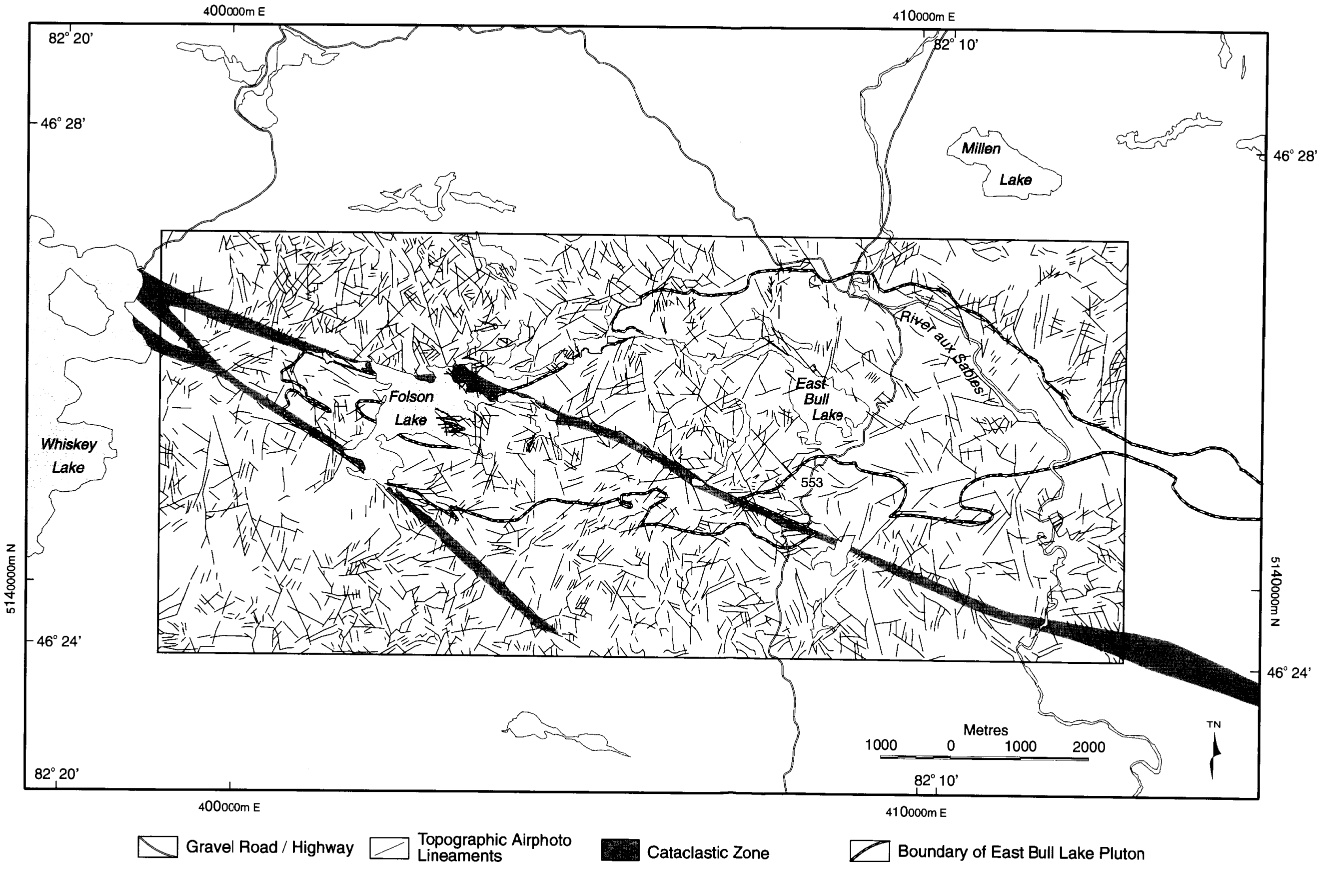


FIGURE 6-2: Topographic Airphoto Lineament Map of the East Bull Lake Region

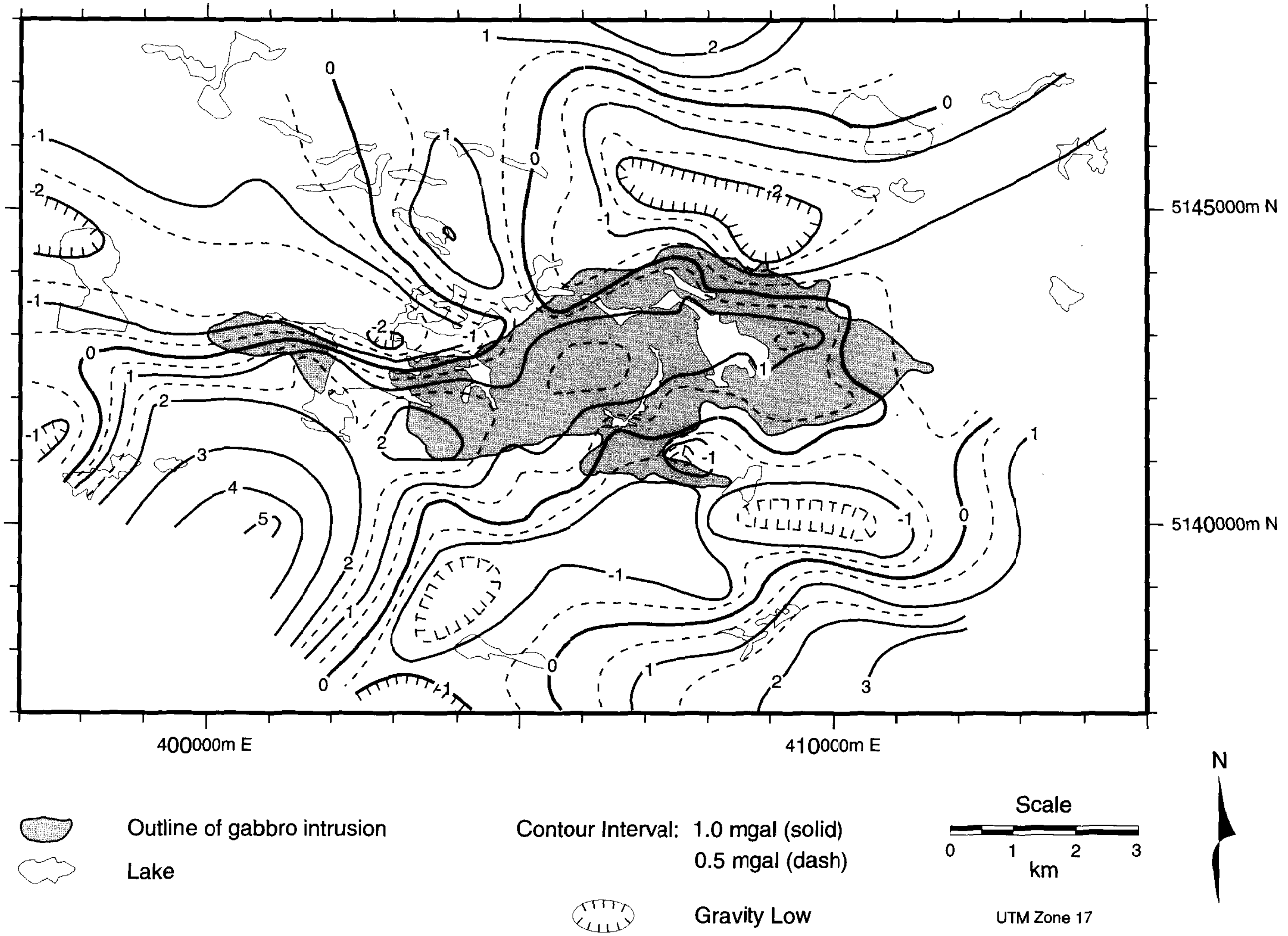


FIGURE 6-3: Gravity Map for the East Bull Lake Region

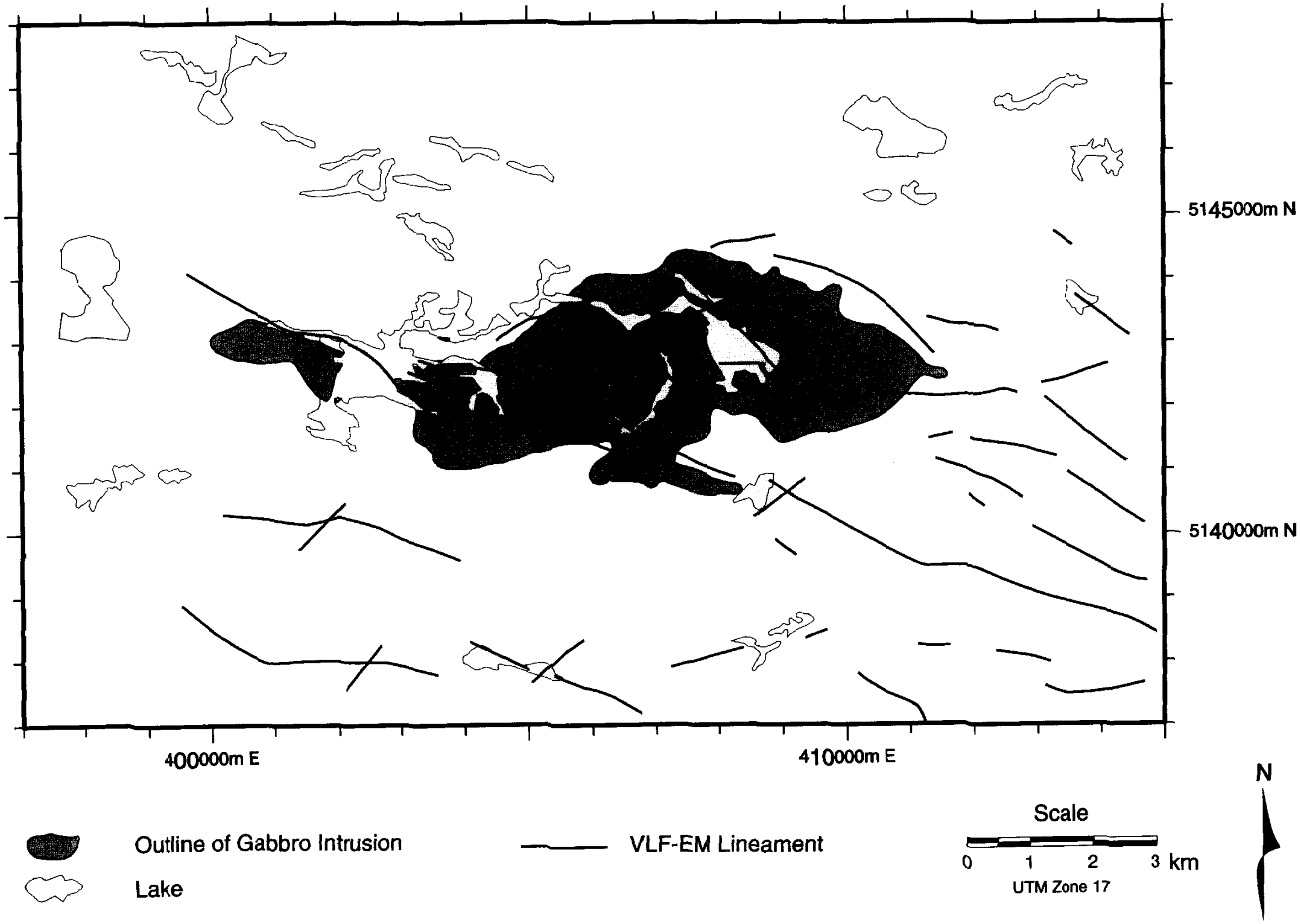


FIGURE 6-4: Lineaments from VLF-EM Survey of East Bull Lake Region

The area was centered on what was thought to be the thickest portion of the pluton.

Based on these reconnaissance scale site evaluation investigations at the East Bull Lake Research Area subsequent detailed surface and subsurface investigations were carried out over the smaller 12 km² study area. The objectives were to: confirm the shape of the pluton; determine the distribution of the rock types and fractures; determine the nature of the fracture fillings; and, investigate the hydrological characteristics of some of the features that were likely to be significant permeable fracture zones (Kamineni et al. 1984, McCrank et al. 1985, Raven et al. 1987). This included thorough investigations at two grid areas within the smaller study area.

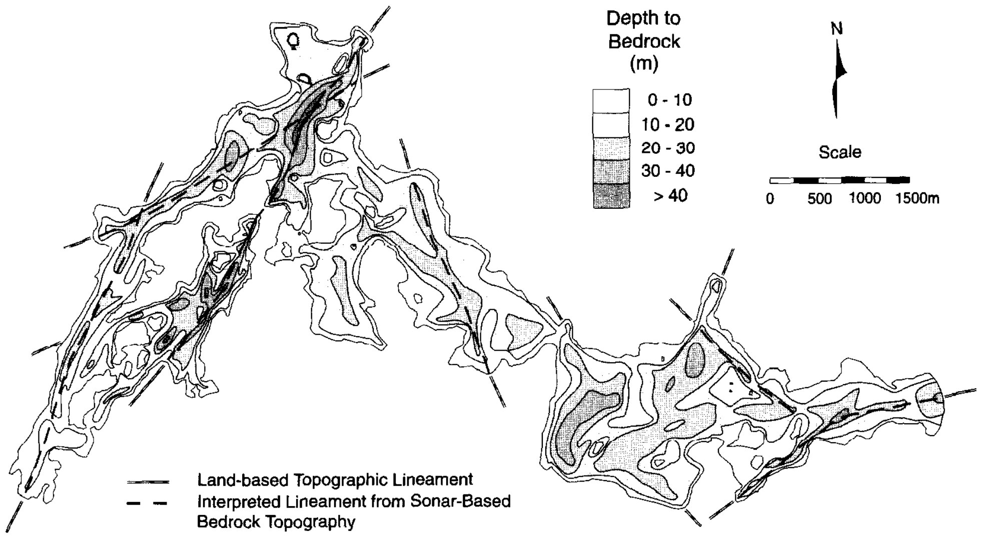


FIGURE 6-5: Eye Lake Bedrock Topography Derived from Sonar Surveys, Atikokan Research Area

Extensive reconnaissance scale site evaluation investigations were also performed at the Atikokan and Whiteshell Research Areas. The methods used were similar to those just described for the East Bull Lake Research Area although some additional methods were used. For instance, at Atikokan measurements were made to determine baseline concentrations of naturally-occurring radionuclides in surface water samples (Larocque and Gascoyne 1986). Regional hydrologic studies were made of watersheds (Thorne 1992). Sonar profile surveys were conducted of lake bottoms to determine the topography of the underlying bedrock surface and to investigate the stratigraphy of the sediments infilling the lake bottoms (Holloway 1985, Holloway et al. 1994). Sonar surveys can provide useful information about recent (postglacial) tectonic movements along faults or fracture zones in the lake bottoms (Shilts and Clague 1992, Shilts et al. 1992). Surveys of the salinity and temperature of lake bottom waters and sediments were also done at Atikokan to locate subaqueous groundwater discharge occurrences (Lee et al. 1994). A map of the bedrock topography beneath Eye Lake at the Atikokan Research Area based on lake bottom sonar survey data is shown in Figure 6.5. The linear features on the lake bottom align with lineaments on land which have been identified from airphotographs and topographic maps (Holloway 1985).

Almost all of the reconnaissance-scale methods, that would be used to characterize a candidate area during site evaluation for a nuclear fuel waste disposal vault, have been applied at the Whiteshell Research Area. The methods were applied either as part of the investigations to select a location for the Underground Research Laboratory (URL) or as part of the research program to develop a regional scale understanding of the groundwater flow conditions of a 750-km^2 area of the Lac du Bonnet Batholith and adjacent rocks. Most of the methods are similar to those already described for reconnaissance-scale site evaluation studies at the East Bull Lake and Atikokan Research Areas. An additional method involves surveying the levels of radon and helium in soil gases to determine if the soils overlie locations of groundwater discharge from the bedrock. This method was tested at the Whiteshell Research Area and was found to be useful for reconnaissance site evaluation (Gascoyne and Wuschke 1990). A similar technique to measure the buildup of helium gas in surface waters during periods of winter ice cover has also proven useful in identifying locations at which groundwaters from deeper flow systems discharge into the surface waters (Stephenson et al. 1992, 1993, 1994, Gascoyne et al. 1993b).

Long-term studies of the spatial and temporal patterns of precipitation and surface water runoff in several watersheds at the Whiteshell Research Area have provided estimates of 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). Studies such as these would be started during the reconnaissance phase of site evaluation.

6.1.5 Summary of Reconnaissance-Scale Site Evaluation Methods

Based on the experience gained from studies at the geologic Research Areas we have determined those methods that could be used for reconnaissance-scale site evaluation studies of candidate areas on the Canadian Shield to identify potentially-suitable candidate sites for a nuclear fuel waste disposal vault. Table 6-1 lists the various reconnaissance-scale methods and describes their application. These methods would be used within an integrated site evaluation program. They would provide the regional information for the candidate area and its surroundings needed to select the locations of small grid areas for thorough surface-based investigations and subsurface investigations in boreholes.

6.2 CHARACTERIZATION OF CANDIDATE AREA USING A PATCHWORK OF GRID AREAS

The initial objective of the period of thorough evaluation of regional conditions is to establish if a site can be found within the candidate area that is technically suitable for locating a disposal vault. The reconnaissance site evaluation 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.

Several small study areas (grid areas) would be located within the candidate area to establish correlations between the inferences drawn from satellite, airborne and surface investigations and what exists in the subsurface. A patchwork of grid areas would provide subsurface information which would be integrated with surface information to develop a three-dimensional understanding of the physical and chemical characteristics of the candidate area.

In parallel with the geotechnical investigations at grid areas, environmental investigations would be conducted to collect data on the baseline conditions in the natural environment. Investigations would be made on the flora, fauna, hydrology, soil, and atmospheric conditions of the biosphere of 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 transport. The conceptual model would form the basis for developing a three-dimensional mathematical model of regional groundwater flow. This model would be calibrated with the field information and used to identify potential locations of discharge of vault contaminants for alternative locations of a disposal vault within the area.

Simplified models would be developed of contaminant movement to the surface from a disposal vault at each of the alternative locations. The geosphere models combined with models of contaminant movement in the surface environment and through the food chain (biosphere models) would be used to help select a suitable location for a disposal vault within the candidate area. The candidate site for the vault would comprise an area of about 25 km^2.

Subsequent detailed investigations would then be designed for the candidate site. These would be used to:

- obtain a much more thorough understanding of the particular conditions at the site,
- identify locations for the exploratory shafts and underground tunnels,
- develop engineering designs of the disposal system taking account of local site-specific conditions and

TABLE 6-1

RECONNAISSANCE SCALE SITE EVALUATION METHODS

Activity	Type of Information	Use
1. Regional Geologic Mapping at a scale of about 1:16000 along traverses .5 km to 2 km apart (more detailed mapping of existing quarried, road cuts or excavations)	Percentage of rock type and spatial distribution of large rock units.	Geometry and size of pluton; folding of pluton; style of pluton contact;degree of granitization.
	Lineament analysis of satellite data, airphotos, topographic maps and, magnetic survey maps.	Fault and fracture zone identification.
	Fracture density.	Relationships to rock type or proximity to faults or fracture zones.
	Fracture orientations, lengths and infilling minerals.	History of fracturing, orientation of stress field in geologic past; locations of faults and fracture zones.
	Collection of rock and fracture infill samples.	Laboratory studies to identify: pressure/temperature (P/T) conditions of pluton emplacement; P/T conditions at episodes of fracturing; absolute dating of pluton deformation history; pluton cooling rates; chemical and mineralogical composition.
2. Airborne Geophysical Surveys	EM and VLF-EMA	Lithologic variations; locate linear features such as faults and fracture zones; map overburden distribution and thickness.

continued . . .

TABLE 6-1 (continued)

Activity	Type of Information	Use
2. Airborne Geophysical Surveys (continued)	Magnetic	Depth, shape and boundaries of lithologic units; map linear anomolies caused by lithology, faults or fracture zones.
	Gravity	Shape, depth and boundaries of pluton; distribution of lithologic units.
	Side-scanning radar surveys.	Map linear anomalies that may be caused by lithology, fault zones or fracture zones.
3. Ground-based Geophysical surveys	Gravity transects	Shape, depth and boundaries of pluton and lithologic units.
	Reflection seismic profiles along transects	Subsurface variations in lithology; identify possible location and orientations of major fracture zones or faults in subsurface.
	Ground penetrating radar surveys along transects on rock outcrops	Location and orientation of low-intermediate dipping fracture zones to 100 m depth.
4. Hydrologic/ meteorologic surveys of watersheds	Temperature, windspeed and direction, evaporation rates, precipitation, runoff rates and distributions, levels of surface water bodies; examine springs and seeps	Drainage, runoff conditions; groundwater recharge/discharge characteristics and rates.

continued . . .

TABLE 6-1 (concluded)

Activity	Type of Information	Use
5. Water chemistry surveys	Chemistry of surface waters,	Ratios of surface water runoff/groundwater discharge (hydrograph separation).
	Chemistry of water in springs and seepage areas	Chemical character of groundwater discharge areas; locate possible areas where groundwater discharge is from deep flow systems.
6. Soil Gas surveys and surveys of gas buildup beneath ice-covered lakes.	He and Rn concentrations	Identify possible locations of groundwater discharge from deep flow systems.
7. Sonar surveys of lake bottoms	Lake bottom bathymetry, thickness of lake bottom sediments, bedrock surface	Identify linear structures in bedrock beneath lake bottoms that may be faults or fracture zones.
		Identify disruptions in lake sediment that may be related to ground- water discharge, gas release, or to post- glacial dislocations along faults.
8. Mapping spatial distribution of thermal conditions in lakes and electrical conductance of lake bottom sediments	Temperature and chemistry of lake bottom waters	Identify possible locations of groundwater discharge.
9. Mapping patterns of flora and fauna	Species and population distribution	Identify population of endangered or sensitive species; identify sensitive habitats.
	Studies of habits of individuals such as deer or moose	Identify possible locations of deep groundwater discharge.

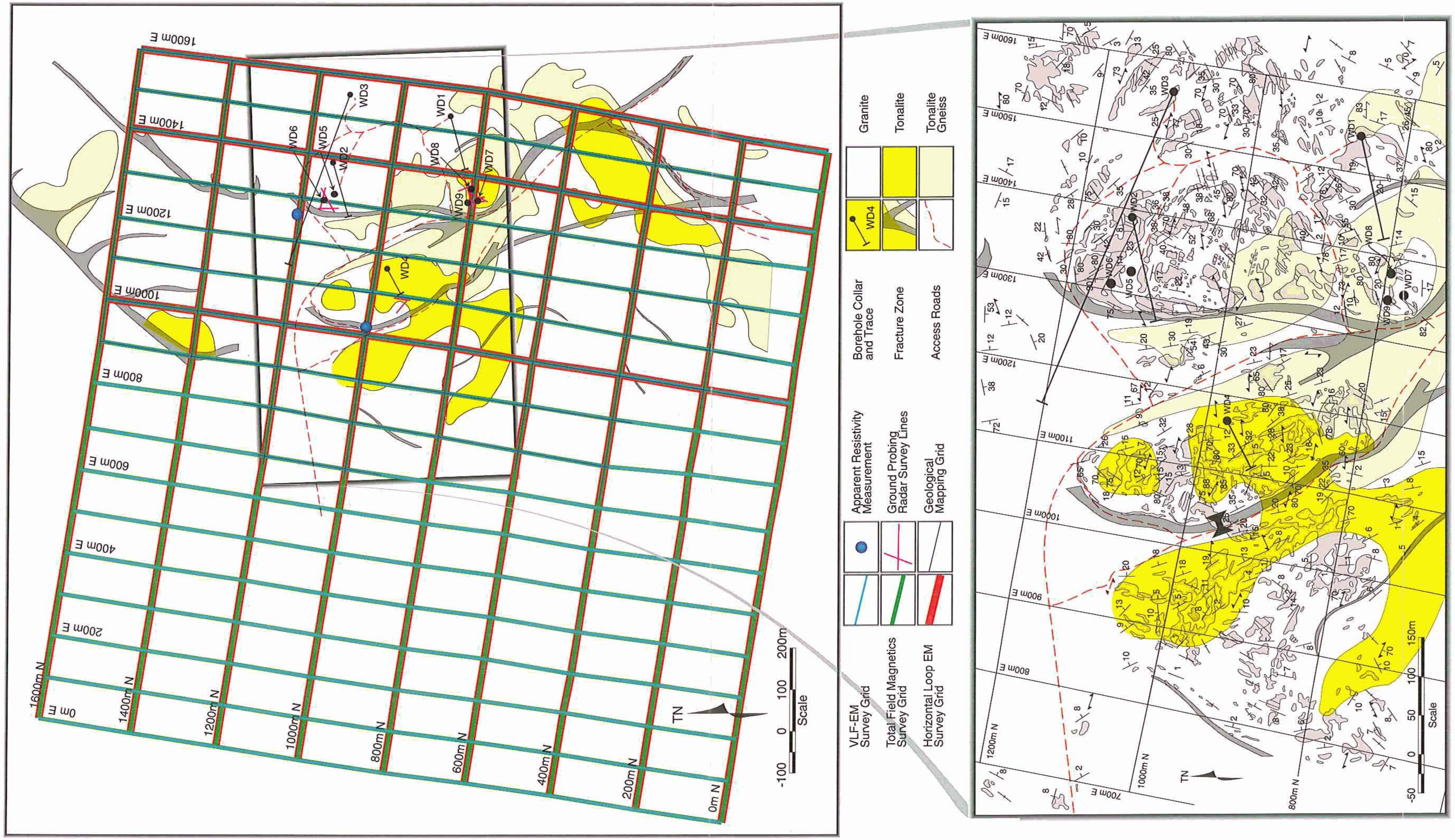


FIGURE 6-6: Grid Area D in the Whiteshell Research Area

- conduct assessments of the long-term safety of alternative disposal system designs at the site. These detailed investigations at the candidate site are discussed in Chapter 7.

Figure 5.4 indicates the locations of grid areas and other study areas used at the Whiteshell Research Area to obtain regional geologic, hydrologic, geophysical, geochemical and hydrogeological data. Figure 6.6 shows one of these grid areas (grid area D) to illustrate the approach that would be used to obtain the data from each grid area.

In addition to the grid areas, studies would also be carried out at other locations in the overall candidate area to obtain geological data on specific structural or lithologic features. For instance, large outcrops, quarries or road cuts in the regional study area would be mapped to provide geologic data along horizontal and vertical exposures. These supplementary studies would have very specific objectives. At the Whiteshell Research Area, small areas of rock outcrop lying along the main lithologic contacts and also in the centre of the batholith were selected and mapped in detail. These studies were used to determine whether the style of deformation mapped in the rocks at the 4.8 km^2 URL lease area was representative of the rocks of the entire Lac du Bonnet batholith, an area of about 700 km^2. For this assessment observations were made on each of these outcrops to record foliations, fold geometry, dykes, ductile fault zones, fracture infillings and kinematic indicators (Brown et al. 1985).

Table 6-2 lists the geologic data that would be collected at grid areas and other geologic study areas and summarizes their use in characterizing a candidate area.

At the Whiteshell and Atikokan Research Areas several thorough mapping studies were conducted of the fractures in horizontal and vertical exposures of the rocks to determine the relationships between sets of fractures with various dips (Brown et al. 1994, Stone et al. 1994).

In many instances it can be helpful to increase or improve the natural exposure of the rock surface or its structural features (fault zones, dykes etc.) at the grid areas by either washing off a thin veneer of soil cover or by excavating shallow trenches through soil-filled lineaments (Stone 1985, Stone et al. 1989, McCrank et al. 1985). 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 East Bull Lake a study was carried out by clearing and washing an area across the Folson Lake Fault, to allow detailed mapping to be done across the fault at a scale of 1:10. This detail gave a clear understanding of the physical and chemical nature of the fault zone which could be related to its subsurface hydrogeological properties (McCrank et al. 1985). Studies of cleared outcrops or trenches excavated to expose fault zones are very useful to identify fracture relationships at the grid areas (Stone et al. 1989, Stone 1985). Excavations that expose the subsurface conditions of the various soils and other surficial deposits also provide useful information about the geologic and hydrogeologic properties of these materials (Betcher 1983, Ridgway 1985).

In addition to studying correlations between surface and subsurface geologic and fracture conditions, studies at the grid areas would be used to provide specific information about important surface hydrologic and meteorologic processes that affect how groundwater moves through the rocks and soils at the site. These would include soil moisture flux studies, evapotranspiration studies, and special studies at groundwater recharge and discharge areas to characterize the quantity and distribution of groundwater movement. Thorne (1992) provides examples of these types of studies from the Whiteshell Research Area.

Radar reflection surveys would be used at the grid areas to probe the near surface of the rockmass for structural discontinuities. In granitic rocks these discontinuities are commonly caused by water-filled fractures, but radar reflections may also be generated from boreholes, excavations in the rockmass or changes in lithology. Generally, sparsely fractured or moderately fractured rock is much more resistive and has a lower dielectric constant than the fracture zones. This contrast results in reflection and refraction of radar pulses when the radar signal encounters fracture zones. The application of the radar reflection method and its use in mapping fractures in hard crystalline rocks has been described by Annan and Davis (1976), Ulriksen (1982), Olsson et al. (1987), Anderson et al. (1987), Soonawala et al. (1990) and Holloway et al. (1993). 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. 1993).

Research has indicated that the radar survey method is particularly useful in detecting low-dipping fracture zones beneath rock outcrops that can be traced to nearby topographic lineaments (Holloway et al. 1993, Ejeckam et al. 1994, Holloway and Mugford 1990). The method has also been used to infer the location of major low-dipping fractures to depths of about 80 m prior to drilling boreholes at the grid areas (Holloway et al. 1993, Stevens et al. 1994). To illustrate the method, Figure 6.7 presents an example of a radar reflection survey on a granitic outcrop at the URL grid area at the Whiteshell Research Area. There is excellent agreement between the location of fracturing seen in the upper 70 m of the nearby borehole M-10 and the various reflectors seen in the surface radar reflection data shown in Figure 6.7.

6.2.1 Borehole Investigations at Grid Areas

Borehole investigations are essential to acquire subsurface information. Boreholes would be drilled at the grid areas to obtain an understanding of regional conditions for the candidate area and at the candidate site to understand local conditions. A wide variety of investigations would be conducted in these boreholes. Boreholes would be drilled into the overburden and into the rock at grid area locations to provide information about particular geological, geophysical or hydrogeological features. In some cases the grid areas would be chosen to locate boreholes 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 grid areas were selected to examine these types of regional features

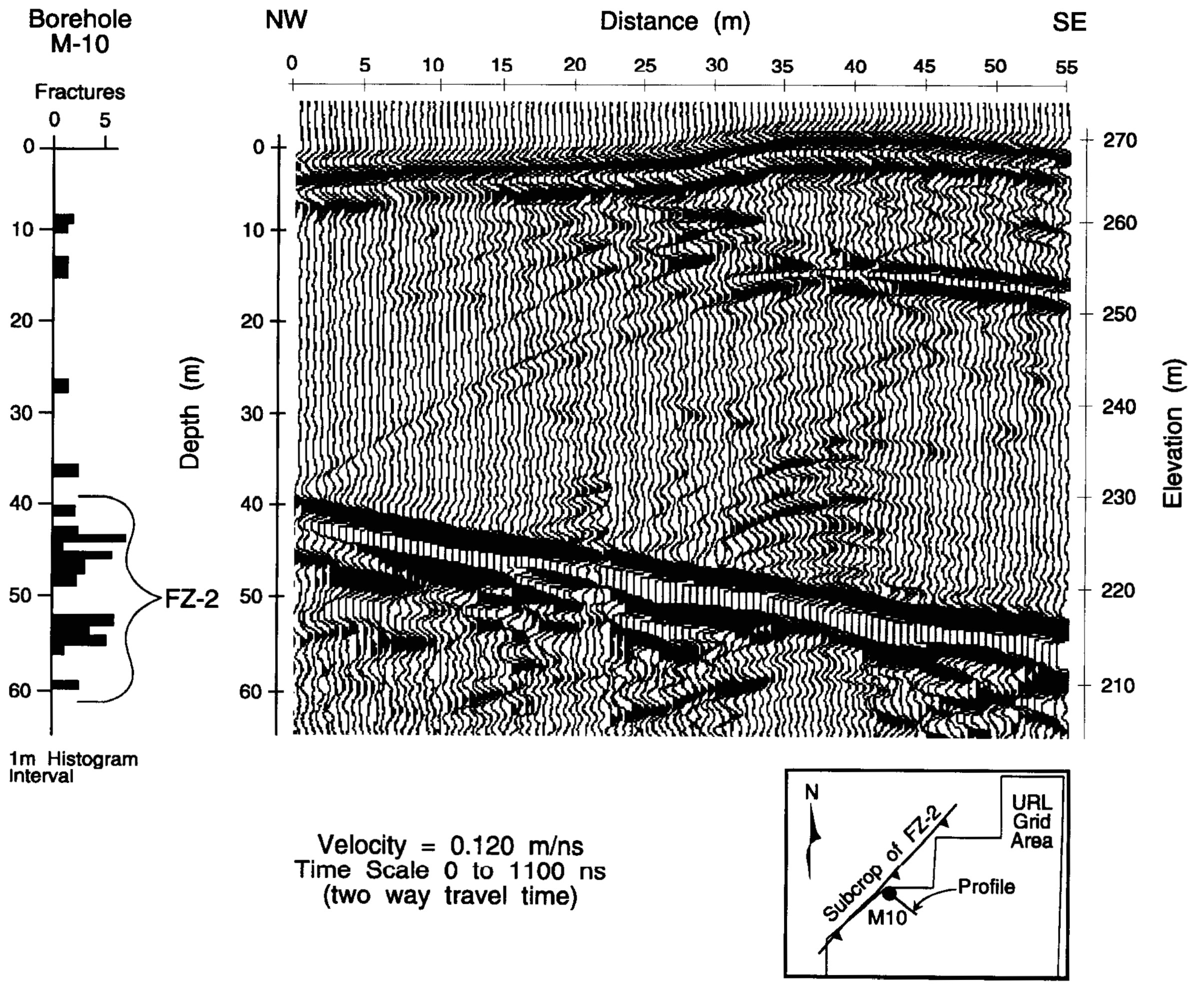


FIGURE 6-7: Radar Profile near Borehole M-10 at the Underground Research Laboratory Site

TABLE 6-2

GEOLOGIC DATA COLLECTED AT GRID AREAS AND GEOLOGIC STUDY AREAS

Type of Data	Use
1. Rock types; distributions, interrelationships and relationships to fracturing.	- Determine lithologic structure of pluton. - Determine relationships or controls on development of fracturing or faulting.
2. Large-scale lithologic layering or folding.	- Helps define pluton shape. - Determine any effect on faulting or fracturing such as relationships to location, orientation and density of fracturing. - Helps define deformation and stress history.
3. Xenolith style, orientation and shape.	- Helps define deformation and stress history.
4. Foliations and schlieren.	- Deformation and stress history. - Establish effects on fracture orientation. - Establish relationship to microcrack orientation. - Determination of homogeneity of pluton deformation. - Establish effects on stress measurements.
5. Late magmatic fractures (pegmatites, aplites, quartz veins).	- Establish deformation and stress history. - Determine P/T conditions of formation.
6. Mapping faults, fractures, microcracks dykes and veins - location and geometric characteristics of individual structures. - patterns and geometry of networks of structures.	- Establish history of deformation and stress history. - Determine present day stress orientation. - Establish relationships between style/density and rock types. - Establish geometry of fault zones and related fractures.
7. Rock and fracture specimens for laboratory examination.	- Establish P/T conditions of pluton emplacement. - Establish P/T conditions at episodes of fracturing. - Dating of deformational history and establish pluton cooling rates.

by borehole investigations. Other grid areas might be chosen to investigate the subsurface conditions at locations that appear to be intrablock areas, away from large fault zones and lithologic contacts. One of the grid areas at the Atikokan research area was selected to examine such an intrablock area within the Eye Dashwa pluton (P.A. Brown and Rey 1985, 1986).

It is impossible to specify a priori how many grid areas might be required at any candidate area during site evaluation. Similarly it is not possible to specify how many boreholes would be required at these grid areas to characterize the regional hydrogeological conditions in order to construct and calibrate a model of large-scale groundwater flow for the area. This will 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 within and between boreholes. Regardless of the complexity, a large number of grid areas and many boreholes will eventually be required to define the geologic structure and monitor the groundwater flow systems of a candidate area for a nuclear fuel waste disposal vault. Information from a large number of grid areas and boreholes will also be needed to help select a suitable location for a disposal vault within the candidate area.

For instance, four boreholes were drilled ranging in depth from 300 m to 900 m at one grid area at the East Bull Lake Research Area, 8 boreholes were drilled ranging in depth from 150 m to 1200 m at 3 grid areas at the Atikokan Research Area and 21 boreholes were drilled ranging in depth from 400 m to 1200 m at 7 grid areas at the Whiteshell Research Area. Although the size scale of the investigations at the Whiteshell Research Area is similar to that likely required for a regional evaluation of a candidate area for siting an actual nuclear fuel waste disposal vault, 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. Rather they were designed to expand the detailed investigations at the URL to the regional scale within the constraints imposed by the distribution of crown land on which investigations could be done. They do however, illustrate the borehole investigations that would be performed in evaluating a large candidate area for siting a nuclear fuel waste disposal vault.

The methods for the drilling, logging, instrumentation, testing and sampling of the shallow boreholes drilled into the overburden materials have been adapted from well established procedures and are described by Betcher(1983), Ridgway (1985), Thorne (1990b), and Thorne (1992). However, the methods adopted for the drilling, logging, instrumentation, testing and sampling of the deep boreholes into plutonic rocks were not previously well established. These have evolved during the research and development programs at the various geologic research areas since 1975 and are discussed in more detail below.

6.2.2 Deep Borehole Drilling

The initial deep boreholes drilled into the rock during site evaluation would be drilled in a manner that would allow the collection of a continuous sample of the rock. For boreholes at the geologic research areas we adapted the diamond core drilling methods commonly used in Canada for hard rock mineral exploration and mining applications. Most boreholes were diamond-drilled as 76-mm diameter (NQ size) boreholes using triple-tube, wireline core recovery methods. Larger 96-mm diameter (HQ size) boreholes were used when in situ rock stress measurements were to be made in the boreholes.

No oils, muds or other additives would be used as lubricants for the diamond drilling, and only clean water from nearby surface ponds or streams would be used for cooling and flushing. A non-toxic dye tracer could be added to the drill water to identify the presence of drill water during subsequent groundwater sampling from the borehole. Alternatively, naturally-occurring tritium (^3H) or other chemical constituents in the surface water could be used as tracers for the drill water. Techniques for distinguishing the drill water from the groundwater are described by Ross and Gascoyne (1993a,b).

We have found a gravity-based method of core orientation to be most reliable. Consequently, most of the boreholes at the research areas have been drilled from surface at an inclination from vertical. This is commonly a 75° plunge from horizontal but flatter inclinations have been used when the lithologic and structural targets were expected to have near-vertical orientations in the subsurface.

The orientation of each length of core with respect to the inclination of the borehole would be recorded during the drilling. A thorough description of the location, orientation, and character of fractures and a range of other structural and lithological features would be made for the core as soon as it is recovered. This record is referred to as a core log. Evidence of high in situ stresses, such as core discing would also be recorded on the core log. One very important fracture observation that would be made on the core is the degree of openness of the fractures. Open fractures are those that show visual evidence of currently being open to groundwater flow. They can be identified by a number of different indicators such as: a loss of drill water pressure during the drilling; the fracture surfaces being discontinuous when fitted together; and open interconnected pore spaces or vugs (Ejeckam et al. 1987).

Immediately after the drilling was completed, a directional survey would be carried out in the borehole using a gyroscopic or similar method to determine the final orientation of the full length of the borehole. Once the directional survey was completed the core orientation information would be translated into true spatial coordinates (Sikorsky 1991). Figure 6.8 shows an example of a summary geologic core log of a borehole illustrating the type of information that would be recorded during the core logging. Figures 6.9 and 6.10 show presentation formats for fracture location, orientation and infilling data.

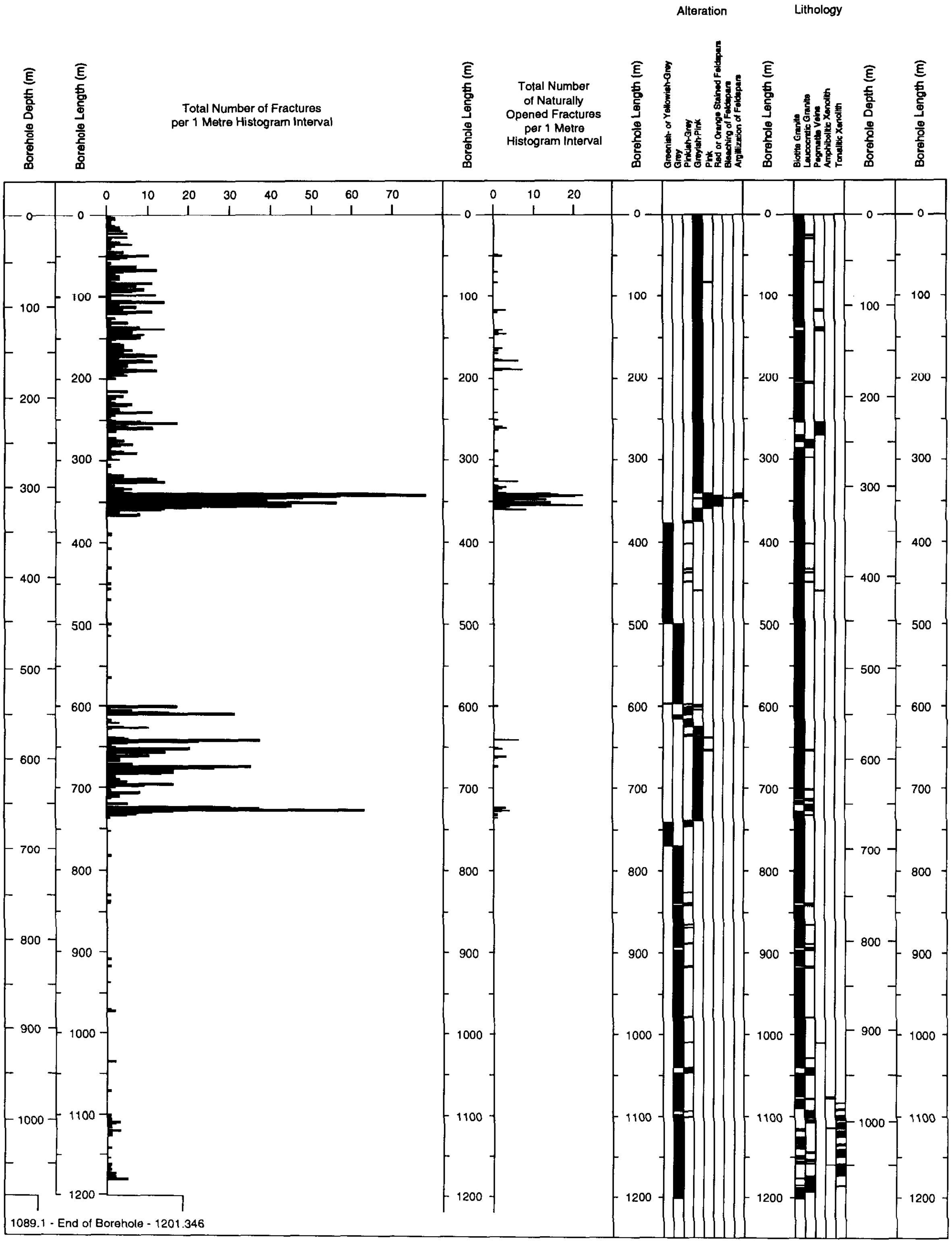


FIGURE 6-8: Summary of Core Log for Borehole WA-1

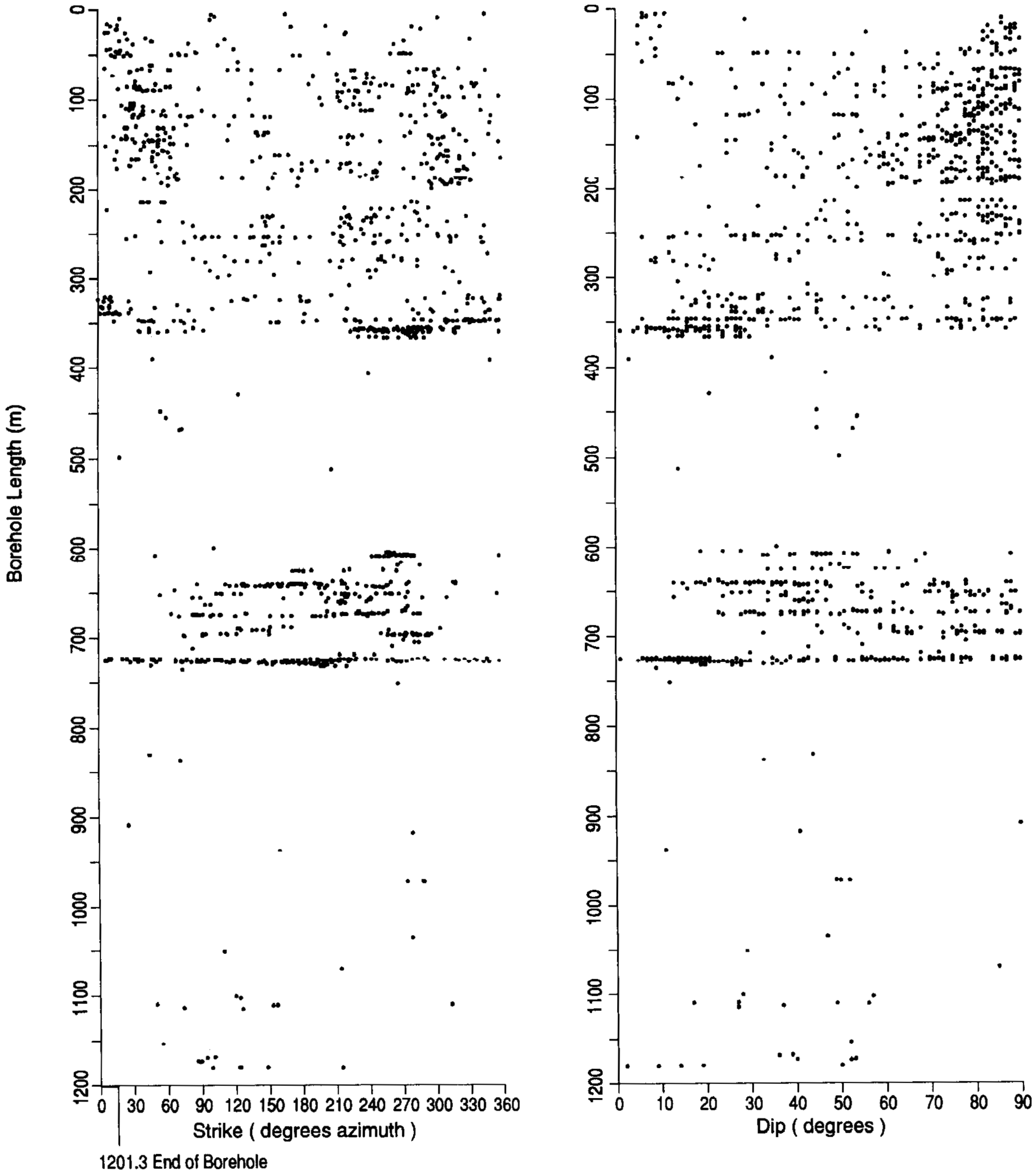


FIGURE 6-9: Scatter Diagram of the Strike and Dip of Fractures in Borehole WA-1

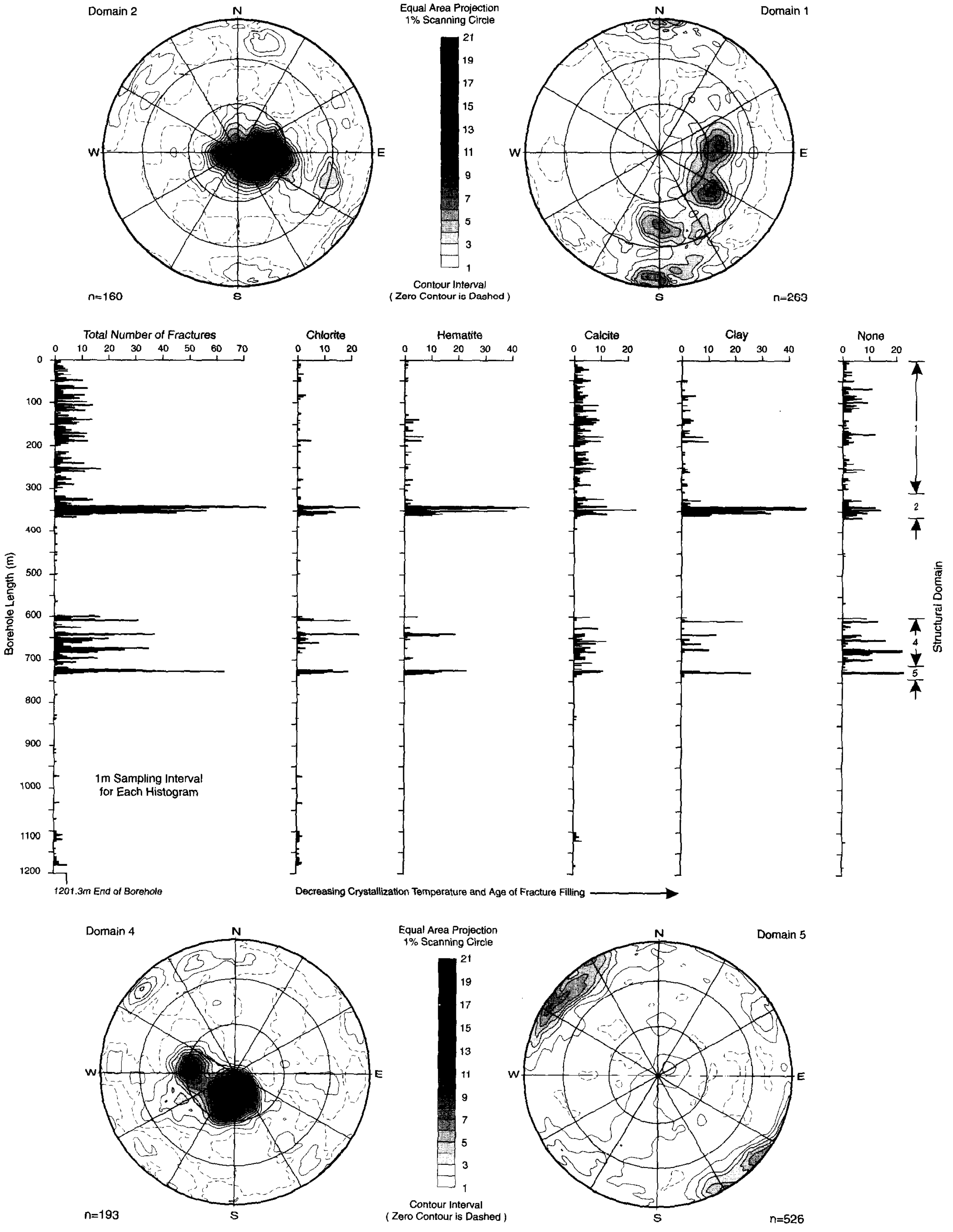


FIGURE 6-10: Fracture Orientation and Fracture Filling Plots of Borehole WA-1

Samples of the core from the boreholes would be selected for laboratory examination to determine their porosity and pore structure properties, permeability, strength, elastic properties, magnetic properties and thermal properties (Soonawala et al. 1982). Other samples would also be taken 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, Kerrich and Kamineni 1988, Griffault et al. 1993). Samples of minerals that are exposed to groundwater in permeable zones or on the surfaces of open fractures would be collected and studied in the laboratory to determine if they would interact to retard the movement of contaminants from the nuclear fuel waste (Vandergraaf 1982, Kamineni et al. 1982b, Vandergraaf and Ticknor 1993, Kamineni and Lemire 1991).

The sample distribution scheme shown in Figure 6.11 provides core sample specimens for the various laboratory rock property tests. Most of the rock property measurements are performed on core samples without open fractures, however special samples would be obtained at and near intervals of open fracturing in the borehole for studies of fracture infilling minerals and rock alteration. Table 6-3 lists the laboratory tests that would be done to determine the rock properties.

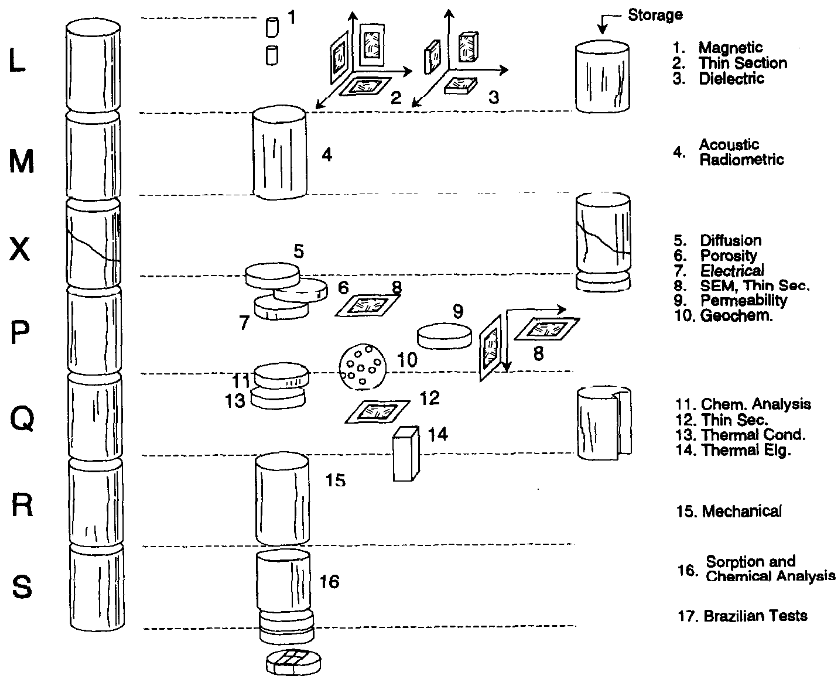


FIGURE 6-11: Schematic of Core Sampling Distribution

It would be preferable to make hydrogeological and hydrogeochemical measurements in a borehole after drilling is completely finished and when the core log and geophysical logs are available to help in planning where these measurements should be made. However, in some cases it may be necessary to interrupt the drilling of a borehole to determine the permeability of a borehole interval or to collect samples of the groundwater encountered. Situations such as encountering severe rubble zones where grouting is required to advance the borehole would warrant this approach. Methods have been developed and tested for obtaining hydrogeological information during the drilling of boreholes (Davison 1980, Raven 1980) as well as in the boreholes after they have been completely drilled (Davison 1981, Raven 1980, Lee et al. 1983, Davison 1984a, Raven et al. 1987, Stevenson and Broadfoot 1994). These methods are discussed in more detail later in Section 6.3.3.

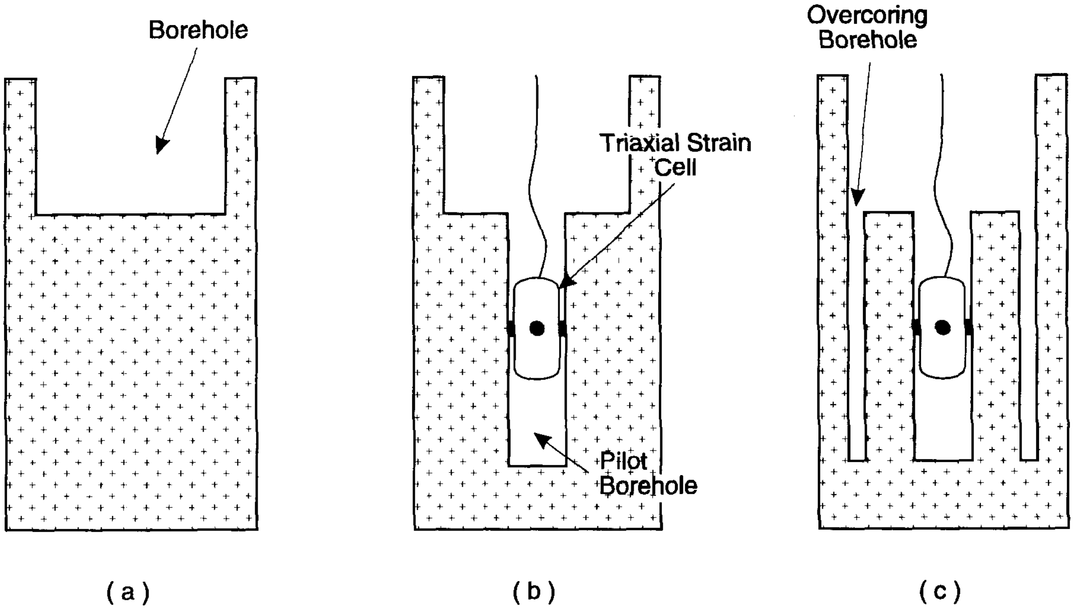


FIGURE 6-12: Overcoring Process for In Situ Stress Measurements

In situ stresses could be determined in boreholes during drilling by an overcoring method. This method requires drilling a small diameter pilot hole ahead of a larger diameter exploratory borehole (Figure 6.12). Strain gauges are either glued on the wall of the pilot hole as with the Swedish State Power Board (SSPB) triaxial strain cell (Christiansson 1989) or the diameter of the pilot hole is monitored with the AECL Deep Borehole Deformation Gauge (Thompson 1990). Once the instrument has been installed in the pilot hole, drilling is continued using a special overcore bit. The deformation of the pilot hole is monitored during the overcoring process. Both of these overcore methods were tested at the URL in 1987. The AECL gauge is preferred because it allows continual monitoring of the overcoring process. This is of great help in interpreting the measured deformations. The AECL gauge has been used

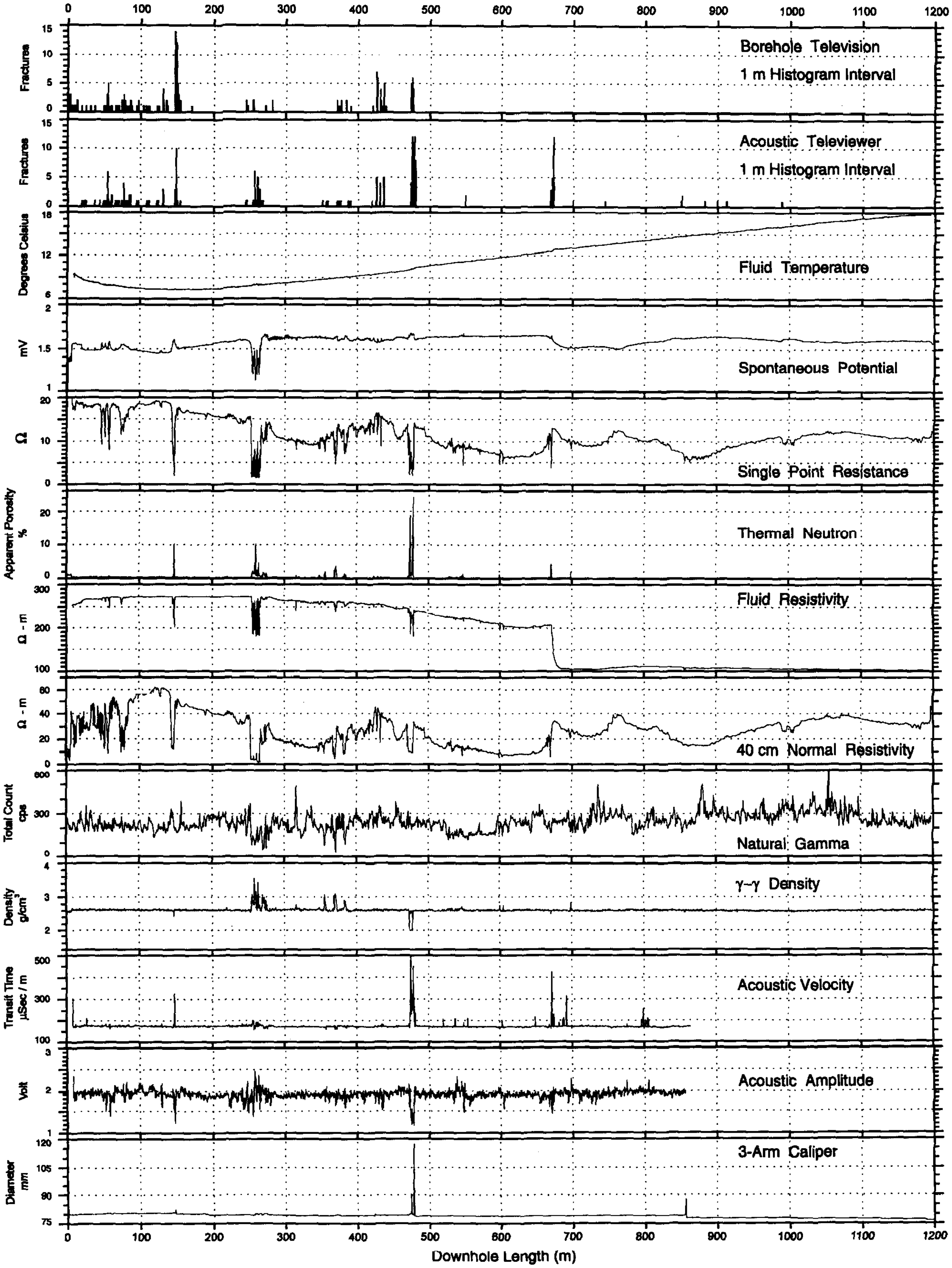


FIGURE 6-13: Borehole Geophysical Logs for Borehole URL-12

successfully to borehole depths of about 220 m. Christiansson (1989) reported that improvements have been made to the SSPB cell that allow for continuous monitoring during the overcoring process. The SSPB cell has been successfully used to depths of about 350 m (Christiansson 1989).

One of the major limitations with using the overcoring method to obtain rock stress information at depth is the rock behaviour itself. The interpretation of deformations associated with overcoring is based on the theory of elasticity which assumes there is a linear relationship between stress and strain. However, in deep boreholes or at high rock stresses, the overcored rock can be adversely affected by the development of stress release microcracking. This microcrack development can cause a nonlinear rock response leading to core discing which can prevent overcoring.

Nonlinear response reduces the confidence that can be placed in both the stress orientation and the stress magnitude results obtained from 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. Discing itself is an indicator of high stress magnitudes but offers no quantitative information on stress orientation although boreholes with a particular orientation in the stress field may be selectively affected. If discing occurs during overcoring hydraulic fracturing can be performed in the borehole after it has been completed to determine the in situ stress state (Haimson and Fairhurst 1969).

After the drilling operation is completed, cleaning and pumping of the water from the borehole would be performed to remove residual drill cuttings and drilling water. In some cases it may be useful to drill the upper 100 m of the boreholes at a larger diameter (96 mm or even 125 mm) to allow the use of high capacity submersible pumps for these cleaning operations.

6.2.3 Borehole Geophysical Surveys

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

Figure 6.13 shows a typical suite of 13 single-hole geophysical logs that are routinely run in deep boreholes at the geologic research areas. The logs shown are from a 1200 m long borehole (URL-12) in the Whiteshell Research Area. 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 record the locations of the fractures and fracture zones encountered in the borehole. The acoustic televiewer log shows that major fracture zones occur at 145-155 m, 472-482 m and 668-674 m in this borehole. Less prominent fracture zones occur at 260 m and 420 m, and the logs indicate the interval from 0-160 m is uniformly fractured. Many of the other single-hole geophysical logs

TABLE 6-3

LABORATORY ROCK PROPERTIES TESTS OF CORE SAMPLE SPECIMENS

Rock Property (descripiton or use)	Method or Test
Pore structure (Description of pore/ fracture structure of the rock matrix)	- Electrical methods to determine rock tortuosity and formation factor. - Porosity and pore spectra methods (surface area, pore aperture, change of aperture with stress). - Micromorphology of pores using scanning electron microscope, ion-probe, petrographic measurements. - Diffusion measurements. - Permeability measurements using water and gas.
High temperature thermal Properties	- Linear expansion up to 600°C. - High temperature, triaxially confined measurements of thermal diffusivity and thermal expansion.
Low temperature thermal properties	- Thermal conductivity. - Thermal diffusivity.
Mechanical rock properties (Strength and deformation properties)	- Uniaxial deformation tests. - Sonic velocity measurements. - Triaxial deformation tests.
Magnetic rock properties (Effects of alteration, used for rock fabric studies)	- Magnetic susceptibility. - Magnetic anisotropy.
Rock crack properties (Supporting data for thermal, magnetic and pore-structure measurements)	- Petrographic examinations of microcracks. - Compressional and shear wave velocity measurements under various confining pressures.
Chemical and geochemical analyses (Data to study interaction of groundwater and wall rock minerals and retardation of radionuclides)	- Mineralogy of rocks, pores and fractures. - Sorption properties of rock forming minerals and minerals lining fractures and pores.

such as spontaneous potential, resistivity, density (gamma gamma), acoustic velocity, fluid resistivity, temperature and caliper also respond to these fracture zones.

The caliper logs respond only if there is an increase of greater than about 1 mm in the diameter of the borehole wall over the interval of fracturing. For example, only the fractures in the interval from 472-482 m in this borehole cause an anomaly on the caliper log. All the electrical and nuclear logs, except the natural gamma log, clearly indicate the locations of the main fracture zones. In this example the fluid resistivity in the borehole begins a decline immediately below the fracture zone at about 260 m, and there is a very large drop in fluid resistivity below the fracture zone at 660 m. These drops in fluid resistivity are caused by increases in the salinity of the borehole water due to saline groundwater entering the borehole from the deeper fracture zones.

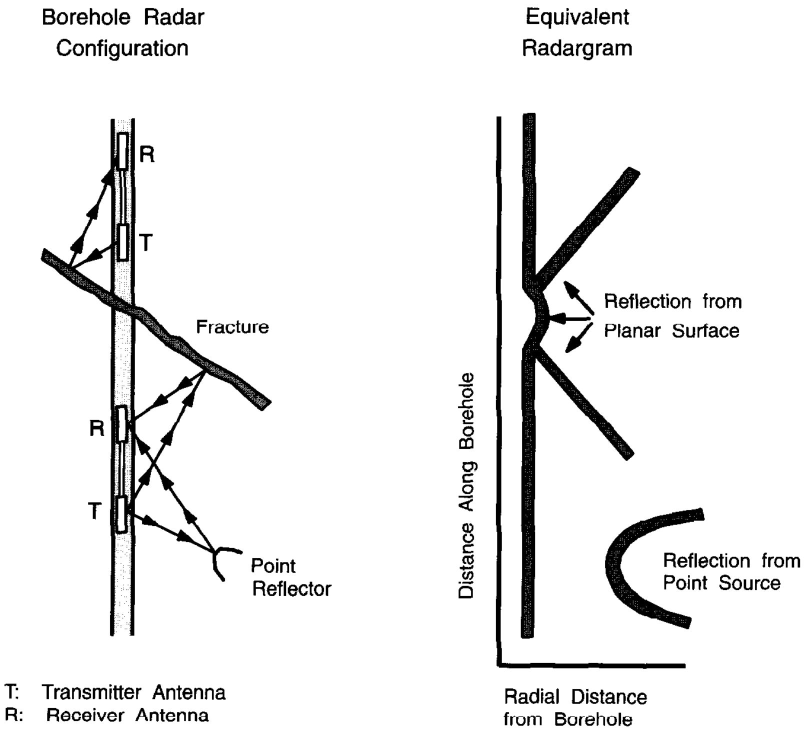


FIGURE 6-14: Schematic of a Typical Borehole Radar Survey Configuration and Its Equivalent Radargram

The temperature of the borehole water also increases with depth as is expected due to the natural geothermal gradient in the rock. There is a temperature inversion in the top interval from 0 to 150 m in the borehole where the temperature decreases with depth. This is a thermal feature typical of most areas that were covered by continental ice sheets during the last glacial advance over the Shield (Drury and Lewis 1981, Drury 1986, Drury and Taylor 1987).

About 95% of the core from borehole URL-12 has a granitic lithology, so the logs from this borehole do not provide many examples of the effects of lithology on geophysical logs although these effects have been observed on the logs from many other boreholes (Davison et al. 1984, Soonawala et al. 1990). However, responses due to minor occurrences of tonalite and amphibolite, which are rich in mafic minerals, can be noted on the neutron-neutron and density logs of this hole.

The single-hole geophysical logging techniques discussed so far measure 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, a single hole borehole radar survey system can be used.

The borehole radar survey system comprises a radar transmitter, a receiver, a signal control unit for communication with the borehole probes and a computer for storage, processing and display of the data. In a single-hole radar reflection survey the transmitter and receiver antennas are moved along the same hole at a fixed separation distance (we generally use 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 radar maps depending on the geometry of the reflectors. Point reflectors give rise to hyperbolic reflections while reflections from fracture planes are represented by lines as shown in Figure 6.14.

Radar surveys in boreholes in granitic rocks can be used to trace fractures up to a distance of 60 to 80 m away from the boreholes. Examples of the radar surveys from boreholes URL-14 and URL-15 at the WRA are shown in Figure 6.15. These boreholes are located 130 m apart. The total number of fractures logged in the core of the boreholes are shown in the figure along with the lithologic variations (Sikorsky 1994). The correlation of the zone of open fractures located at 270 m depth with the reflections mapped by the single borehole radar surveys in these boreholes is clearly visible (Holloway 1990). The borehole radar technique can also be used to carry out borehole radar tomography surveys between boreholes separated by distances up to 150 m. An example of radar tomography is shown later in section 6.3.1 where we discuss multiple-borehole geophysical characterization methods.

The direction of vertical flow of groundwater in open boreholes can be determined during geophysical logging by means of a high sensitivity heat-pulse flowmeter (Paillet and Hess 1987), or by analyzing anomalies on the borehole temperature log and observing changes in the anomalies with time by repeated logging (Drury 1984a, b).

Impeller flowmeter logs can also be used to help identify the location of the more permeable fractures in the boreholes. In impeller flowmeter

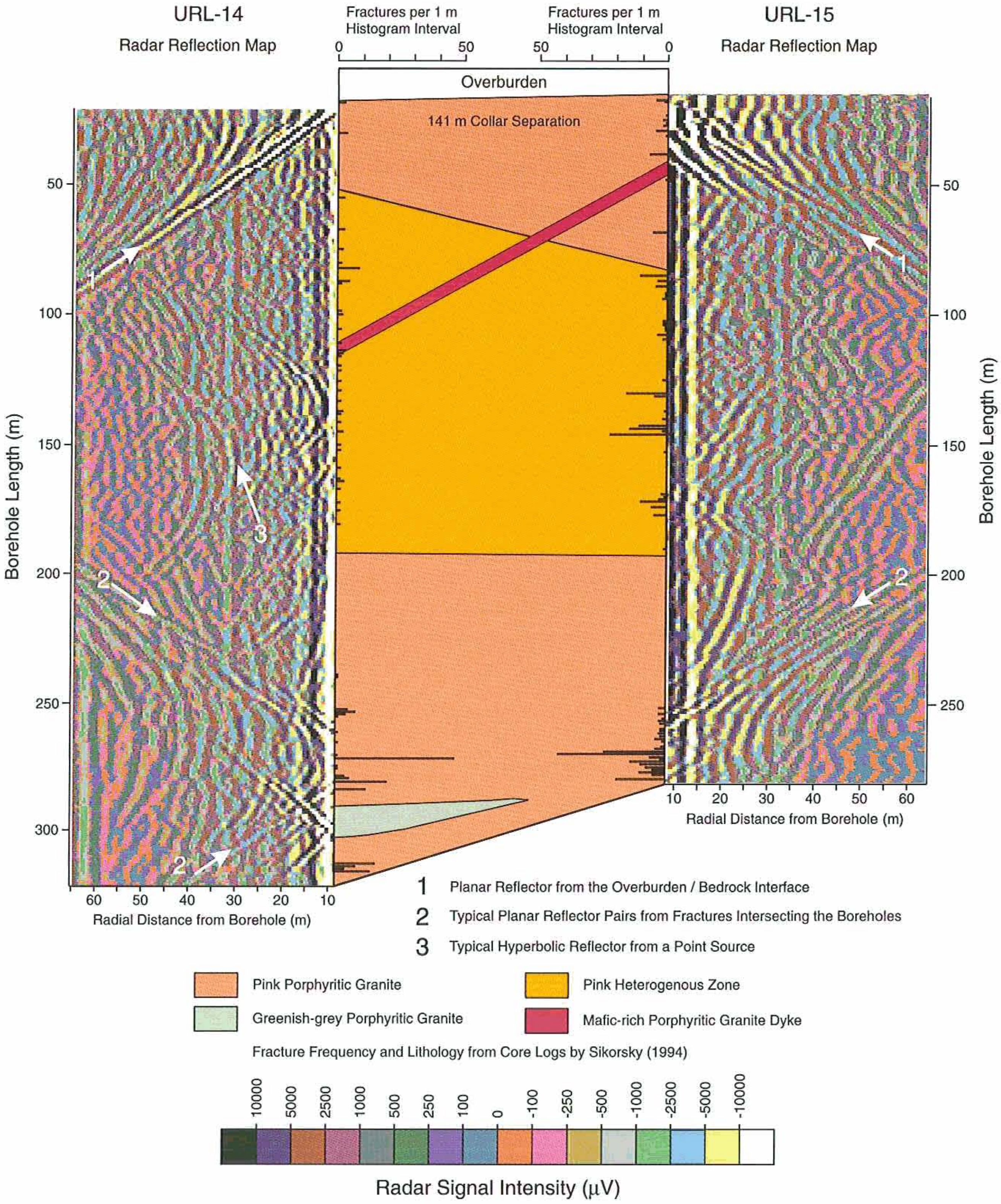


FIGURE 6-15: Radar Reflection Maps from Radar Surveys in Boreholes URL-14 and URL-15

logging, both the descending and ascending runs are recorded. When water enters a borehole and flows vertically, the blade rotation rate will decrease if the logging direction is the same as the flow direction. Conversely, the rotation rate will increase if the logging direction is opposite to flow direction. An example of impellar flowmeter logs of a fractured section of a borehole at the WRA is shown on Figure 6.16. In this example the location of the most permeable portion of the fracture zone at 324 m is evident on the flowmeter logs.

6.2.4 Hydrogeological Tests

As mentioned earlier, hydrogeological tests would usually be done in the boreholes after they have been completely drilled, the core has been logged and single-hole geophysical surveys have been run. The information from the borehole core and the geophysical logs would be used to select the appropriate borehole intervals for the hydrogeological tests. The test intervals would be selected to determine the hydrogeologic properties of the fractured and non-fractured or sparsely-fractured intervals of the boreholes.

Two or three of the initial boreholes drilled at a candidate area would be selected for hydrogeological testing at fixed intervals along the entire borehole length. This procedure would provide a broad data base of permeability values for all fracture domains identified in the boreholes at the candidate area. Because this type of testing is more time consuming and costly than testing of selected intervals, it would usually be done before a good understanding of the hydrogeological conditions was available. As the understanding of hydrogeological conditions of an area improves, the hydrogeologic testing in subsequent boreholes would focus on evaluating specific borehole intervals.

Special equipment has been developed by AECL Research for hydrogeological testing in deep boreholes. It consists of either modified diamond drilling equipment (referred to as a workover rig) or an umbilical cable/winch system to raise and lower the hydrogeological test equipment (Figure 6.17).

The 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 (Figure 6.18). By analyzing the variations which occur in the groundwater pressure and volume during the tests, the permeability of the region of the rock surrounding the test interval can be calculated. Other hydrogeological aspects such as porosity, spatial variations or boundaries in the permeability conditions surrounding the borehole, and natural groundwater pressure conditions can also be inferred from the test data (Lee et al. 1983, Davison 1984a, Raven et al. 1987, Stevenson and Broadfoot 1994).

The hydrogeologic testing would include methods performed in single boreholes as well as in multiple boreholes. Single borehole testing would be used to evaluate the hydrogeologic conditions of both fractured

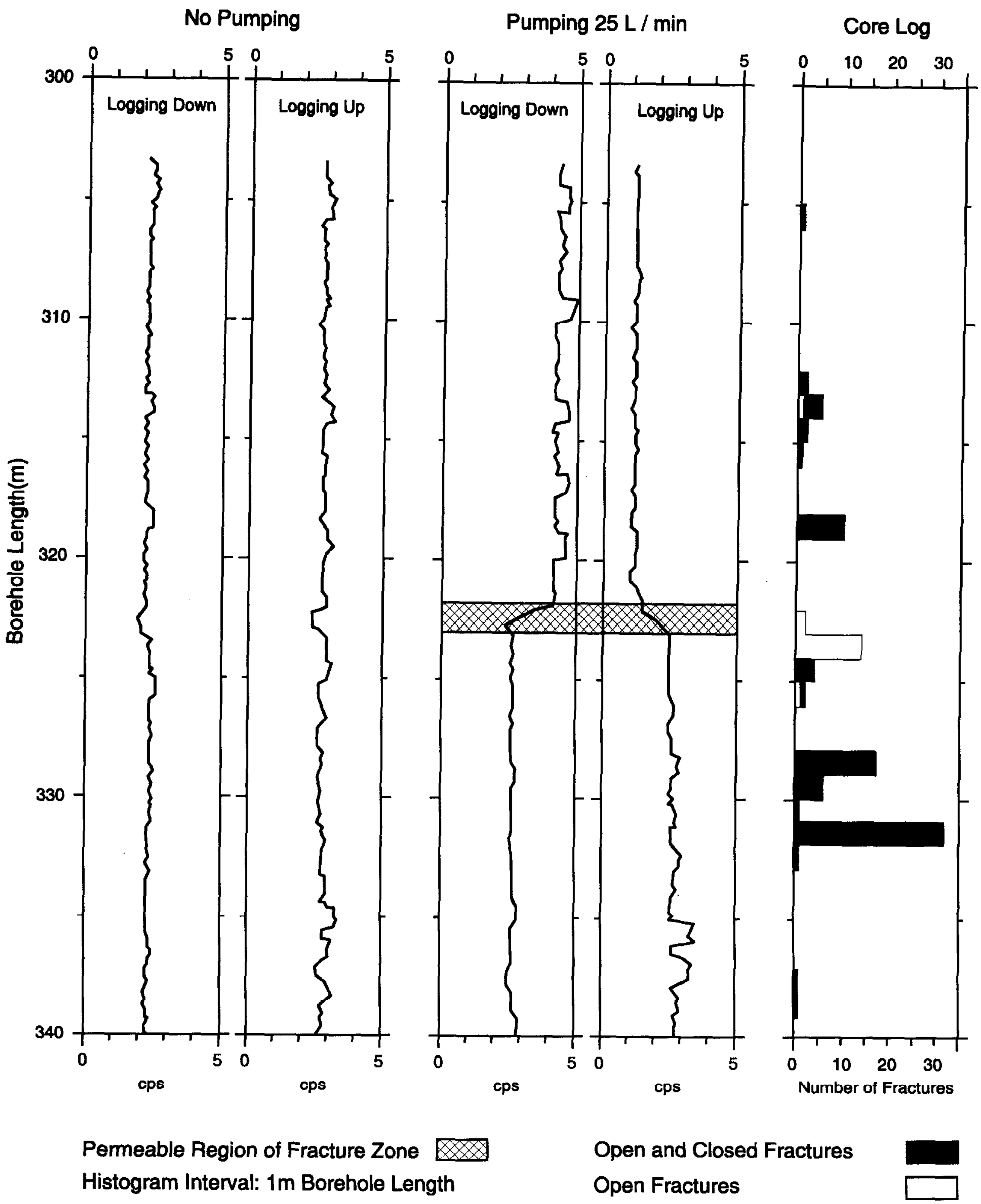


FIGURE 6-16: Impeller Flowmeter Logging in borehole WN-12

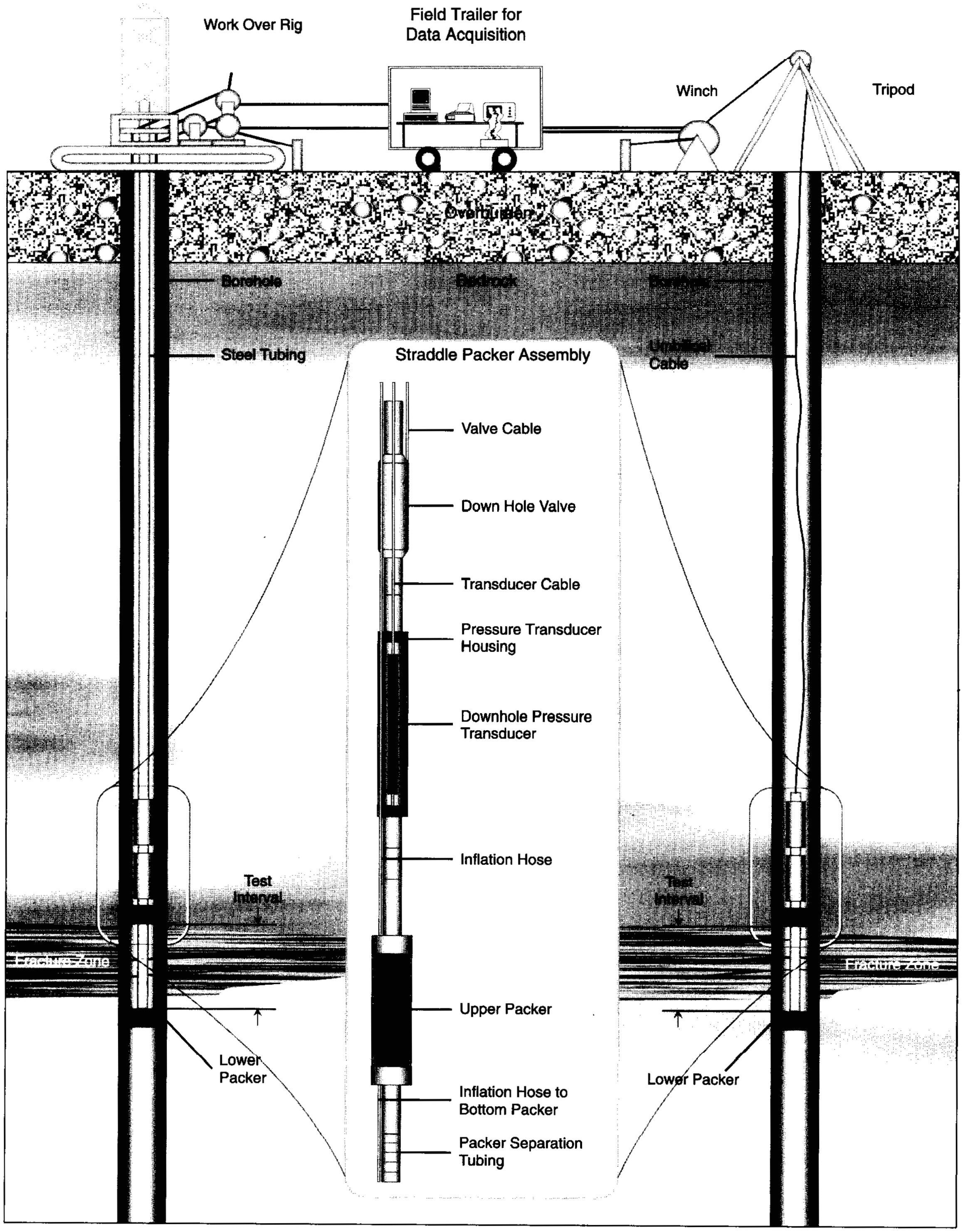


FIGURE 6-17: Hydraulic Testing Equipment; Work Over Rig or Umbilical Cable

and unfractured zones along the borehole, whereas multiple borehole tests would usually be performed at the fractured zones.

In single-borehole hydrogeologic 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 are usually due to permeability variations near the borehole (near-field boundary conditions). During multiple-borehole 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 tests may show the effects of permeability variations over distances greater than several hundred metres from the borehole being tested (Davison 1984b, Davison and Kozak 1989). The multiple-borehole hydrogeologic tests are discussed further in Section 6.3.2.

The hydrogeologic testing methods can be used to determine the permeability of intervals in deep boreholes for a wide range of permeability conditions. Permeabilities as low as about $\sim 1\times10^{-21}$ m^2 (1×10^{-14} m/s) and as high as about 1×10^{-10} m^2 ($\sim 1\times10^{-3}$ m/s) can be determined using straddle packer equipment and data analysis methods developed by AECL Research for the CNFWMP (Davison 1981, Raven 1980, Raven et al. 1987, Davison 1982, Lee et al. 1983, Stevenson and Broadfoot 1994).

Methods used for determining the permeability of low permeability test zones can be different from those used for high permeability zones. For example, a constant pressure/variable flow injection test or a pulse test can usually be used in low permeability test zones, whereas a constant flow/variable pressure injection or withdrawal test can be performed in high permeability test zones (Raven 1980, Davison 1981). Depending on the test type, hydrogeologic test data can be analysed using a number of flow models, which represent either steady-state or transient pressure conditions (Davison 1980, Raven 1980, Stevenson and Broadfoot 1994).

Single borehole transient pressure test data can be analysed 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 (Kozak and Davison 1992, Lee et al. 1983, Stevenson and Broadfoot 1994). Computer-assisted type curve fitting methods such as that of Gringarten (1986) can be used to match the transient pressure data.

Figure 6.19 shows the permeability data obtained from single borehole hydraulic testing of a deep borehole at the Whiteshell Research Area. In this example the permeability surrounding the borehole ranges from about 1.5×10^{-13} m^2 ($\sim 1\times10^{-6}$ m/s) at a fracture zone located at 70 m depth to about 1.5×10^{-20} m^2 ($\sim 1\times10^{-13}$ m/s) at an interval of sparsely fractured rock located at about 700 m depth.

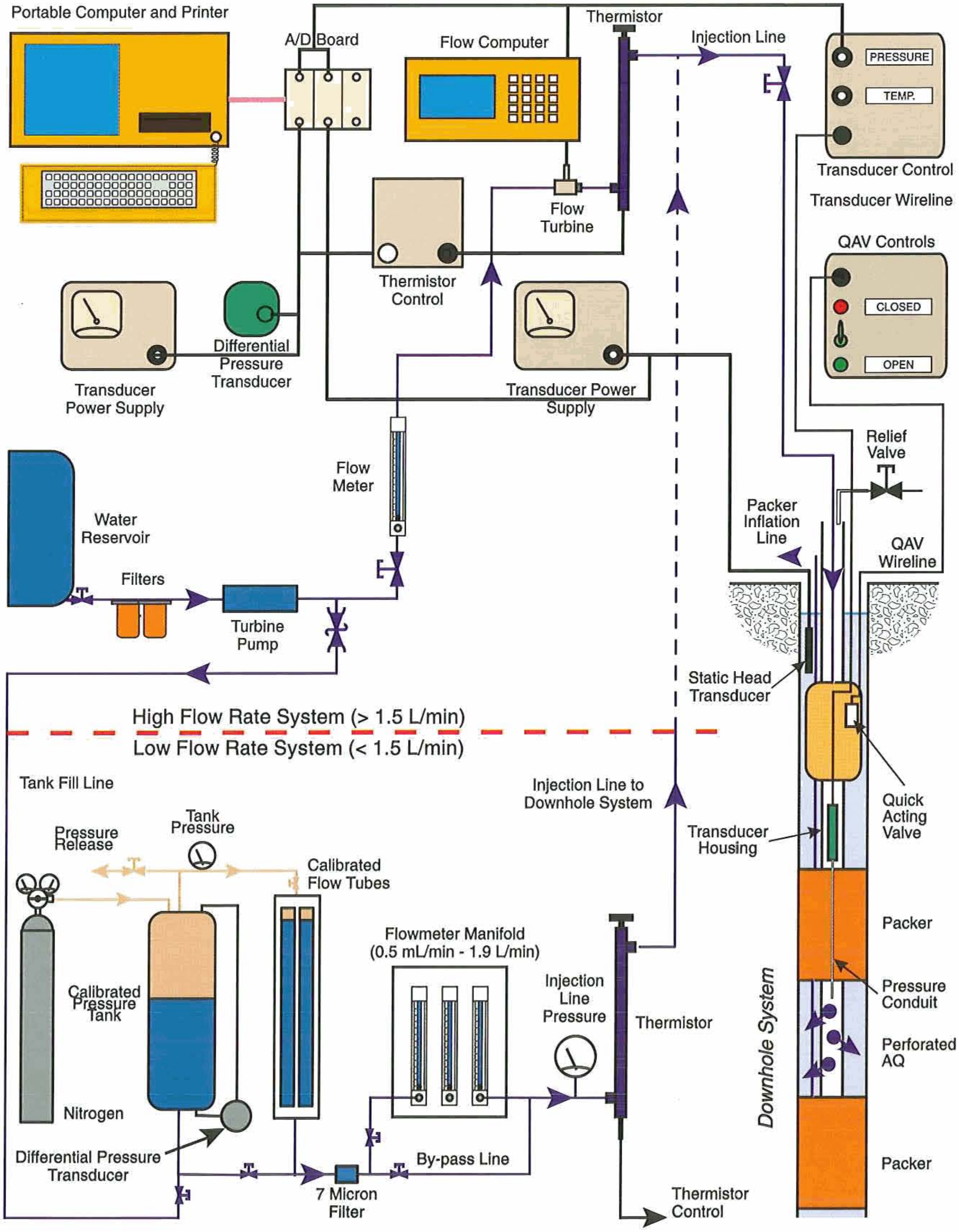


FIGURE 6-18: Hydraulic Testing, Surface and Borehole Equipment System

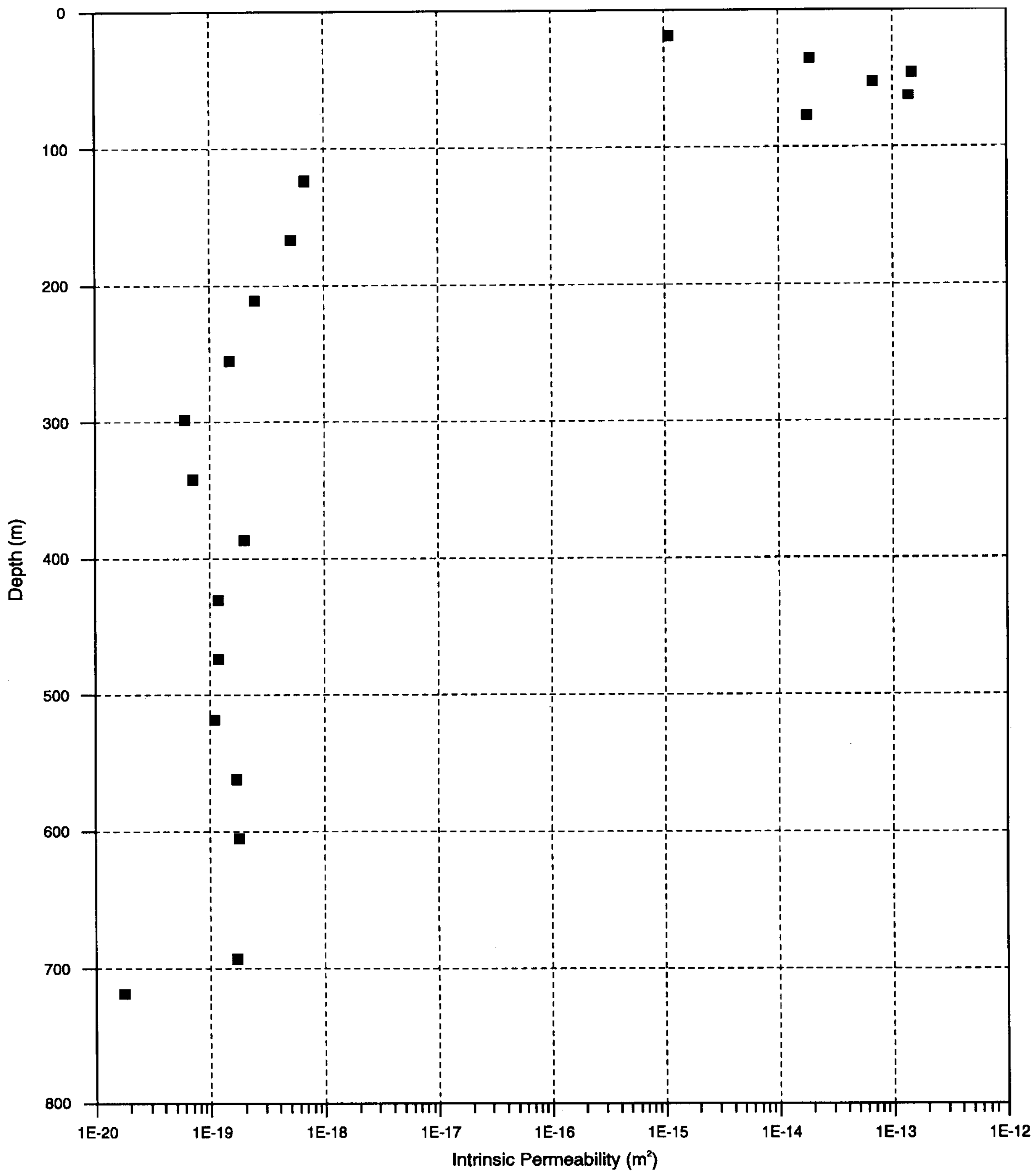


FIGURE 6-19: Hydrogeologic Test Results for Borehole WG-1

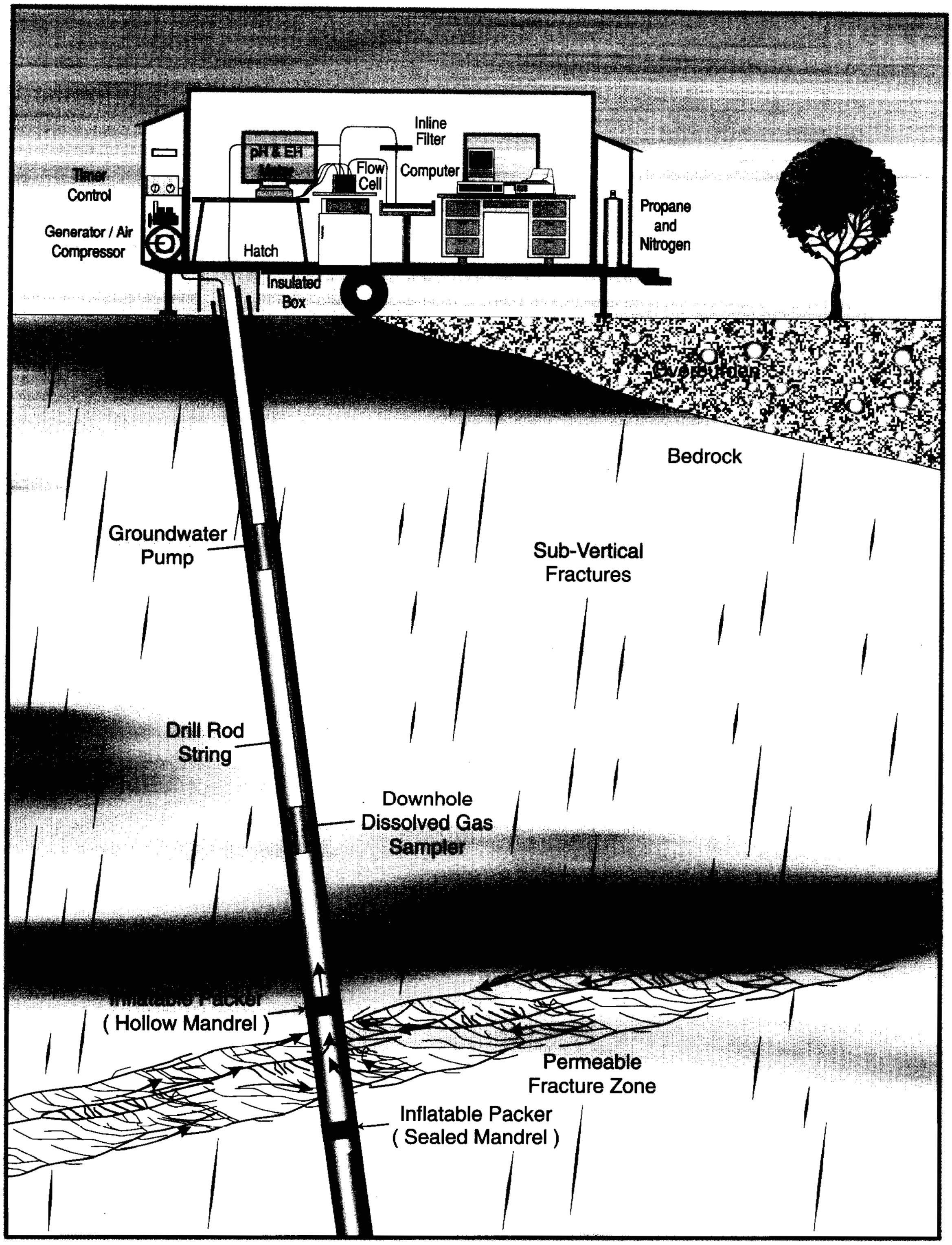


FIGURE 6-20: Sampling Groundwater from a Borehole

6.2.5 Hydrogeochemical Sampling

After a borehole has been drilled, groundwater samples would be obtained to determine the chemistry of the groundwater at various intervals along the borehole. These samples would be collected 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 6.20. Special procedures can be used to ensure that representative samples are collected of the groundwater that exists within the packer interval of the borehole and many different samples are collected and preserved to determine the ionic species, dissolved gases, isotopic character colloidal content and organic content of the water (Gascoyne et al. 1988, Ross and Gascoyne 1993 a,b). The pH and Eh of the groundwater can be measured at the surface using electrochemical probes in a sealed flow-through cell to give reliable estimates of the in-situ conditions.

Table 6-4 summarizes the parameters that would be measured in the groundwater samples 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 is used to delineate rock-water interactions and also to determine the relative age and origin of the groundwater and the dissolved solutes it contains (Gascoyne 1990, 1991, Gascoyne et al. 1991b).

For instance, shallow recharging groundwaters found in most plutonic rock types of the Shield are calcium bicarbonate in composition and quite dilute (Total Dissolved Solids, TDS, is usually below 0.3 g/L). With longer rock contact, sodium content of the groundwater increases and calcium content decreases. This is due to 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 due largely to dissolution of soluble salts (present as fluid inclusions and in pores atom grain boundaries) in the rock. Saline groundwaters rich in chloride and sulphate (TDS > 1 g/L), are generally found below 300 m in all sparsely fractured or moderately fractured Shield rocks that have been studied. More dilute waters may be found deeper than 300 m in fractured zones where groundwater recharge has penetrated from surface along permeable vertical fractures. The saline groundwaters can also be found at shallower depths in areas where deeper saline groundwaters are discharging to surface. Chloride-enriched, saline groundwaters indicate prolonged rock-water contact or mixing with a highly saline groundwater source. The latter may occur in rocks at the margins of the Shield due to the intrusion of brines from adjacent sedimentary rocks. Detailed discussions of the hydrogeochemical characteristics and trends in rocks of the Canadian Shield can be found in Frape and Fritz (1987), and Gascoyne et al. (1987, 1988, 1989, 1991b).

TABLE 6-4

GROUNDWATER SAMPLING, SAMPLE PREPARATION AND ANALYSIS METHODS

Sample	Species/Element	Container	Volume	Filtered	Preservative (Preparation)	Analytical Methods[1]	Laboratory
Anions	HCO_3, SO_4, Cl, Br, F, NO_3, I	Plastic	250 mL	Yes	Refrigerate (4°C)	Titration, IC Colorimetry	HGC[2]
Cations	Na, Ca, Mg, K, Sr, Si, B	Plastic	125 mL	Yes	4 mL/L HCl	ICPS flame AAS	ASB[3]
Trace elements	Li, Fe, Mn, V, Al + others	Plastic	125 mL	Yes	8 mL/L $HN0_3$	ICPS colorimetry	ASB
Dissolved organic carbon	Organic C	Glass	125 mL	Yes	Refrigerate (Ag)	Infrared analyzer	P. Vilks, GRB[4]
Colloids	Colloidal fractions	Plastic	50 L	No	N_2 purge	Tangential flow	P. Vilks, GRB
Environmental isotopes	^2H, ^3H, ^{18}O; ^3H (enriched)	Plastic Glass	125 mL 1 L	Yes Yes	None None	MS LSC	ASB, Univ of Waterloo
Carbon isotopes	^{13}C, ^{14}C	Plastic	4-100 L	No	None (±PC, $BaCO_3$ or in NaOH)[5]	MS LSC AMS	Univ of Waterloo & Toronto
Sulphur isotopes	$S^{18}O_4$, $^{34}SO_4$	Plastic	1-4 L	Yes	None (PC, ion exchange or $BaSO_4$)[5]	MS	Univ of Waterloo
Chlorine isotopes	^{36}Cl,	Plastic	1-4 L	Yes	None (PC, AgCl)[5]	AMS	Univ of Rochester
Strontium isotopes	$^{87}Sr/^{86}Sr$	Plastic	250 mL	Yes	8 mL/L HNO_3	MS	RH McNutt, McMaster Univ
Uranium and radium isotopes	U, $^{234}U/^{238}U$, ^{226}Ra	Plastic	1-4 L	Yes	8 mL/L HNO_3	AS	HGC
Radon	^{222}Rn	Glass vial	8mL	No	None	LSC	HGC
Dissolved gases	H_2, He, 0_2, N_2, CO_2, CH_4, Ar, H_2S	Steel cylinder	50 mL	No	None	MS	ASB
Dissolved inert gases	He, $^3He/^4He$, Ne isotopes	Copper tube	10 mL	No	None	MS	WB Clarke, McMaster Univ

[1] IC = Ion Chromatography,
ICPS = Inductively Coupled Plasma Spectrometry,
AAS = Atomic Absorption Spectrometry,
(A)MS = (Accelerator) Mass Spectrometry,
LSC = Liquid Scintillation Counting,
AS = Alpha Spectrometry

[2] HGC = Hydrogeochemistry Section, AECL, Pinawa

[3] ASB = Analytical Science Branch, AECL, Pinawa

[4] GRB = Geochemistry Research Branch, AECL, Pinawa

[5] PC = Preconcentration (Preparation) done at AECL followed by method used

6.2.6 Hydraulic Fracturing for In Situ Stress Determinations

Hydraulic fracturing can be performed in a borehole to determine the in situ stress conditions. This method requires isolating a section of borehole with a straddle packer system and subjecting the zone to progressively increasing radial fluid pressure until a fracture in the borehole wall occurs (Figure 6.21). 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). It is also assumed 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 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 with hydraulic fracturing in boreholes at the URL showed that below 300 m depth the hydraulic fractures were not coaxial but were nearly perpendicular to the borehole axis. This has prevented successful hydraulic fracturing interpretations below 300 m at the URL. Investigations are underway at the URL to overcome this limitation.

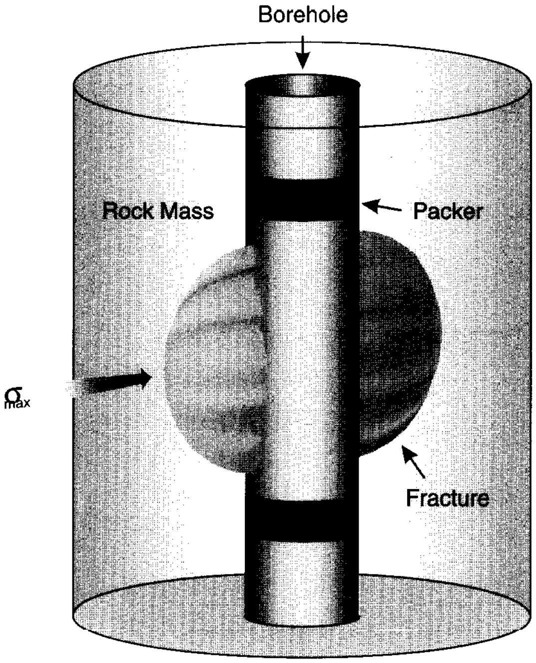


FIGURE 6-21: Hydraulic Fracturing

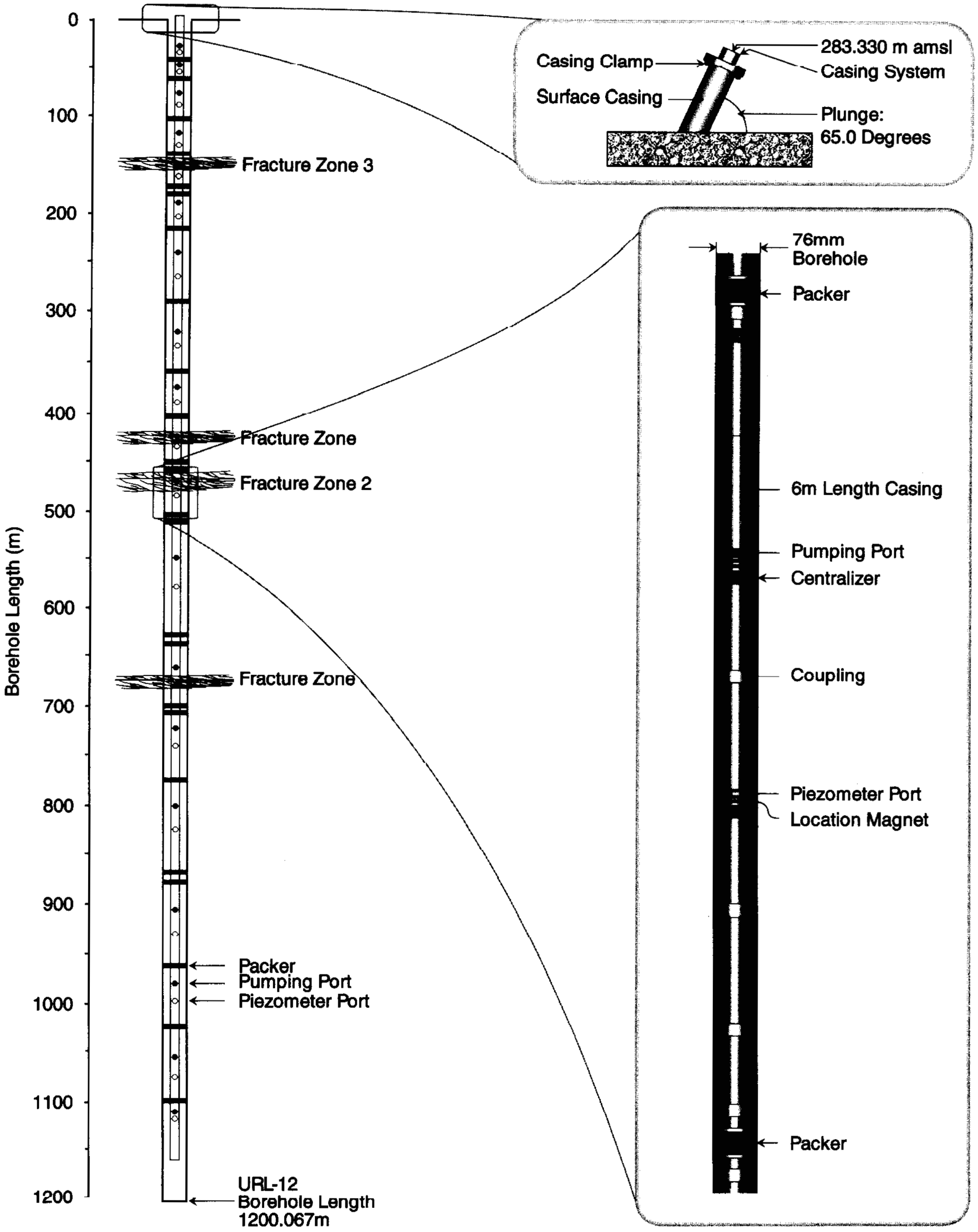


FIGURE 6-22: M-P Casing System in Borehole URL-12

6.2.7 Hydrogeological Monitoring Systems

In order to prevent mixing of groundwater from different permeable intervals in the borehole, yet provide long-term access to zones of interest, different intervals within the boreholes would be isolated from one another as soon as possible after the borehole drilling, testing and sampling activities were completed. Semi-permanent, multiple packer (M-P), casing systems can be installed within the boreholes for this purpose (Davison 1984a). These 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 zones of interest in each borehole. Each module consists of a pair of inflatable packers that isolates an interval of the borehole from the rest of the

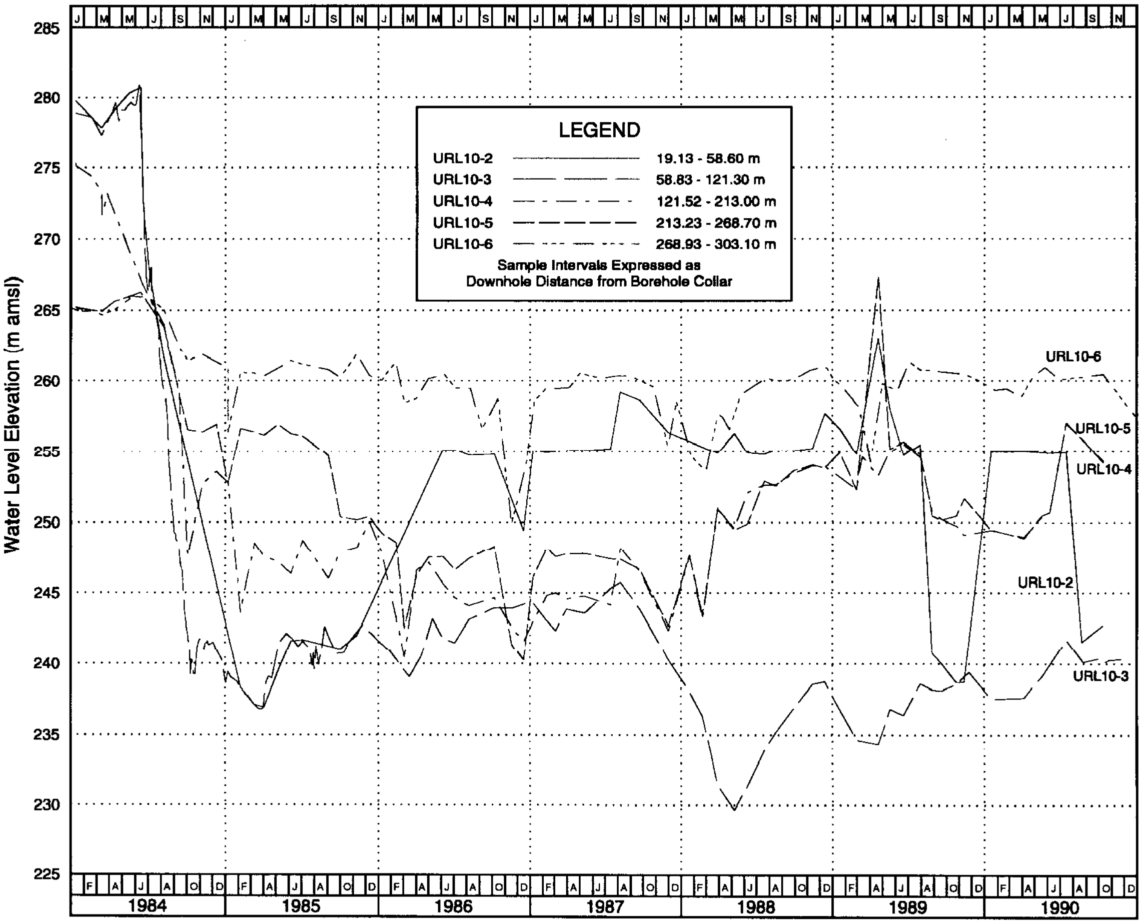


FIGURE 6-23: Example of Piezometric Pressure Record for Borehole URL-10

borehole and contains two valves which can be operated to provide access through the casing to the interval. One of the valves is operated to provide short term access to the interval for recording groundwater pressures; the other valve is operated to provide long term access for groundwater sampling or hydrogeological testing. Figure 6.22 shows an example of a M-P casing system installed within a 1200 m long borehole located at the Whiteshell Research Area. Seventeen different intervals representing different degrees of fracturing on different lithologic units are isolated within this borehole for hydrogeological monitoring and testing and for hydrogeochemical sampling. The grid area studies at the Whiteshell, East Bull Lake and Atikokan Research Areas used these modular M-P casing systems to isolate from 10 to 30 different intervals in each deep borehole.

Groundwater pressure can be monitored within these M-P casing systems on a regular basis. These records can be used to determine how long it takes the pressure conditions to readjust to equilibrium conditions from the disturbances created by borehole drilling, logging and testing. This monitoring also records the long term groundwater pressure fluctuations that occur at each monitoring interval. If the rock in the monitoring interval has low permeability, it can take several months or even years for the groundwater pressures in the monitoring intervals to readjust from the drilling and testing disturbances.

Long term records of groundwater pressures in the M-P casings provide useful information about the groundwater pressure distribution in the borehole. These records also provide information about how these pressures respond to natural factors (earth tide and barometric cycles, rainfall occurrences, long term climatological cycles) or to man-induced factors (borehole drilling in the vicinity, groundwater pumping tests). Figure 6.23 is a long term groundwater pressure record from monitoring an M-P casing system installed in a borehole near the URL excavation at the Whiteshell Research Area.

We have had no difficulty obtaining reliable groundwater pressure measurements from intervals in the M-P casing systems that isolate borehole zones having permeabilities greater than about 1×10^{-18} m^2 ($\sim1\times10^{-11}$ m/s). However, measurement difficulties have occurred in intervals where the rock has a permeability lower than about 1×10^{-18} m^2 ($\sim1\times10^{-11}$ m/s). At these lower permeability values movement by molecular diffusion would be expected to begin to dominate over movement by fluid advection. Not only does it take several years to obtain a stable pressure reading in these monitoring intervals, the pressures which are recorded are often unusually high. We are confident that most of the anomalous groundwater pressures reflect the actual in situ pressure. These may be caused by in situ rock stress conditions or reflect a slow dynamic response to paleohydrogeologic conditions. However, it is also possible that some anomalous readings are caused by the measurement method itself. We are currently pursuing studies to resolve these issues.

6.2.8 Summary of Methods for Investigating Single Deep Boreholes

Table 6-5 is a list of the various activities and surveys that can be used to obtain subsurface geologic, hydrogeological, geochemical and geomechanical information from deep boreholes drilled from ground surface.

6.3 MULTIPLE BOREHOLE INVESTIGATIONS AT GRID AREAS

The investigations that would be conducted within single boreholes would identify zones of fracturing and determine whether the zones were permeable in the vicinity of the borehole. However, the information obtained would usually represent either a point sample or a line sample of the subsurface conditions. It would not be used to extrapolate conditions very far from the boreholes. Multiple borehole investigations would be made, within arrays of rather closely-spaced boreholes at the grid areas, to determine if the lithologic and fracture zones identified in one borehole were connected to similar zones in other boreholes in a way that would allow groundwater to move between them. Similarly it would also be necessary to perform tests in the boreholes that could be used to interpolate the conditions in the rock between grid areas. Cross-hole geophysical surveys and multiple borehole hydrogeologic tests are used to determine the continuity of groundwater flow pathways conditions in the rock between boreholes.

6.3.1 Cross-hole Geophysical Surveys

If two boreholes are close enough (within about 400 m), geophysical surveys using the transmission of radar or seismic waves from one borehole to another can be made prior to the installation of the semi-permanent hydrogeologic M-P casing systems. These cross-hole 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; Lodha et al. 1991; Hayles et al. 1992; Holloway et al. 1993).

Cross-hole Seismic Tomography

Cross-hole seismic tomography involves recording a series of seismograms with a source of seismic energy located in one borehole and detectors located in another. Detailed coverage of the rock section between the holes is achieved when numerous locations along the boreholes are used for the positions of the source and the detectors.

Although analysis could be done of reflected signals in tomographic surveys, most analysis so far has focussed on the transmitted signals to determine the conditions between the boreholes. This involves examining the characteristics of the P- or S-wave arrivals after they have traversed the rock between the holes. Travel times and amplitudes of the direct wave arrivals can be inverted to create images of the seismic properties of the region between the boreholes. The inversion is done using computer-assisted tomographic imaging techniques similar to that

TABLE 6-5

CHARACTERIZATION METHODS USED IN DEEP BOREHOLES

Activity/Survey	Information
1. Logging drill core	- Geologic description of lithologic variations. - Location, orientation, geometric characteristics of fractures. - Nature of fracture infillings and alteration.
2. Thermal logging of fluid in borehole	- Geothermal gradient, locations of inflows and outflows of groundwater in borehole.
3. Flow logging of fluid in borehole	- Locations of more permeable intervals of borehole.
4. Acoustic televiewer survey	- Location, orientation of fractures and other irregularities in the borehole wall such as due to lithologic variations or stress-induced breakouts.
5. Borehole television camera survey	- Location, orientation of fractures. - Character of fracture infillings. - Lithologic variations.
6. Standard geophysical logs	- Fracture locations. - Salinity of borehole fluid. - Lithology variations.
7. Single hole radar survey	- Location, orientation and extent of large fractures away from the borehole (up to 70 m).
8. Hydraulic fracturing	- Magnitude (and in some cases orientation) of state of stress in rock.
9. Groundwater sampling using straddle packer equipment	- Groundwater chemistry variations.
10. Hydrogeological testing using straddle packer equipment	- Permeability and storage conditions of near field surrounding borehole.

continued . . .

TABLE 6-5 (concluded)

Activity/Survey	Information
11. Installation of multiple-packer (M-P) casing system	- Provides long term access to hydraulically isolated intervals for hydrogeological testing and monitoring and groundwater sampling.
12. Hydraulic tests and geochemical sampling through M-P casing system	- Permeability/storage conditions of near field surrounding boreholes. - Groundwater chemistry variations. (provides data for use in developing an understanding of the large scale groundwater flow conditions).
13. Long-term piezometric pressure monitoring using M-P casing system	- Hydraulic head distribution. (data for use in developing large scale groundwater flow system understanding).

used in diagnostic medicine. One method is referred to as the Simultaneous Iterative Reconstruction Technique (SIRT). A new method has been developed and tested to reduce the synthetic smearing that can affect seismic travel time inversion. This new technique is referred to as the Areal Basis Inversion Technique (ABIT) which gives better resolution between seismic targets when multiple targets exist in the tomogram (Serzu et al. 1994).

The basic design of a cross-hole seismic survey is shown in Figure 6.24. The frequency range needed for cross-hole investigations in plutonic rock is significantly higher than used for conventional earth surface-based exploration seismology, i.e., 0.5-40 kHz rather than 10-200 Hz. Thus, there are important differences between the technology employed in cross-hole work in plutonic rock and that used in conventional exploration seismology.

In the cross-hole seismic survey system developed for the CNFWMP, piezoelectric ceramic transducers are used as the active elements in the source and detector transducers because of their high-frequency response and good impedance match to plutonic rock. This system is also non-polluting to the borehole. The transducers are packaged in metal housings to form downhole probes which can operate in water-filled boreholes over 1000 m deep. In the simplest configuration, the detector probes are not mechanically clamped to the borehole wall and act like hydrophones. For better coupling to rock or for operation in dry boreholes, more complicated probes are used. These have electrically-powered clamping mechanisms to lock the seismically active parts firmly against the sides of the borehole. The source waveform may be a simple pulse, but to achieve maximum transmission range a continuous, coded signal called a pseudo-random binary sequence (PRBS) is used. The PRBS method has noise rejection characteristics superior to the more common swept-frequency methods.

The seismic tomography results from a reconnaissance survey performed in a pair of boreholes at the Whiteshell Research Area, discussed below demonstrate the application of the method for mapping the continuity of fracture zones between pairs of closely-spaced boreholes. These two holes (WB1 and WB2) are separated by 76 m at the collars and diverge to a distance of 200 m at a downhole distance of 750 m (Figure 6.25).

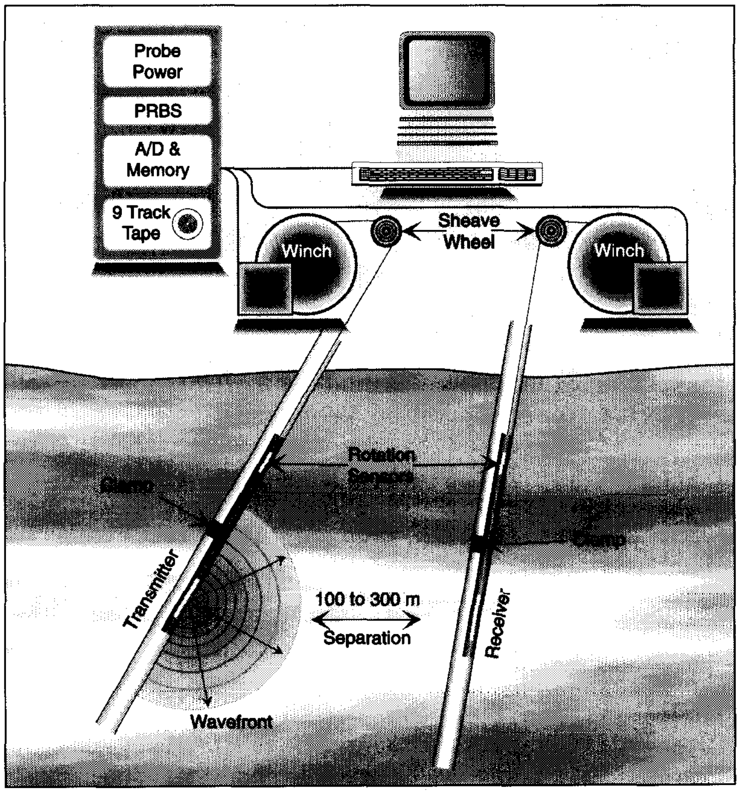


FIGURE 6-24: Cross-Hole Seismic Survey Layout

The survey was carried out with a transmitter in borehole WB2 and a receiver in borehole WB1. The transmitter was moved at 20 m spacings from 30 m to 660 m depth for each receiver location (50, 100, 160, 180, 200, 250, 280, 300, 350, 450, 500, 550, 600, 680 and 740 m depths). A total of 441 rays were shot and 336 of these were used for the final image. The image produced by the Simultaneous Iterative Reconstruction Technique (SIRT) is shown along with the borehole fracture logs in Figure 6.25. The surveys indicate an average P-wave velocity near the surface in the weathered and fractured region of the pink granite to be 5400 to 5700 m/s. The velocities in the sparsely fractured grey granite

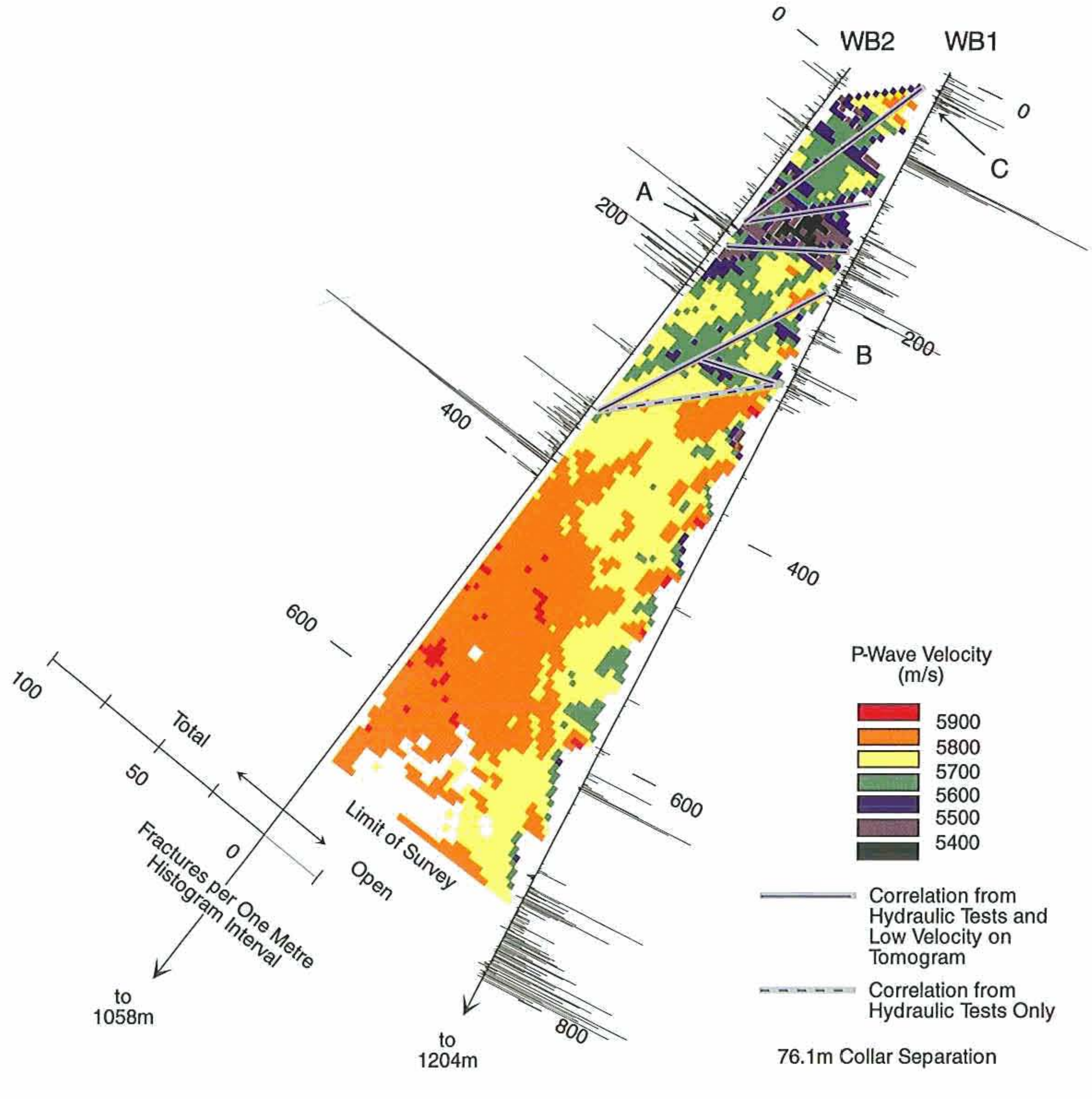


FIGURE 6-25: Cross-Hole Seismic Image of the P-Wave Velocity between Boreholes WB1 and WB2 shown with Hydraulic Test Correlations and Fracture Histograms

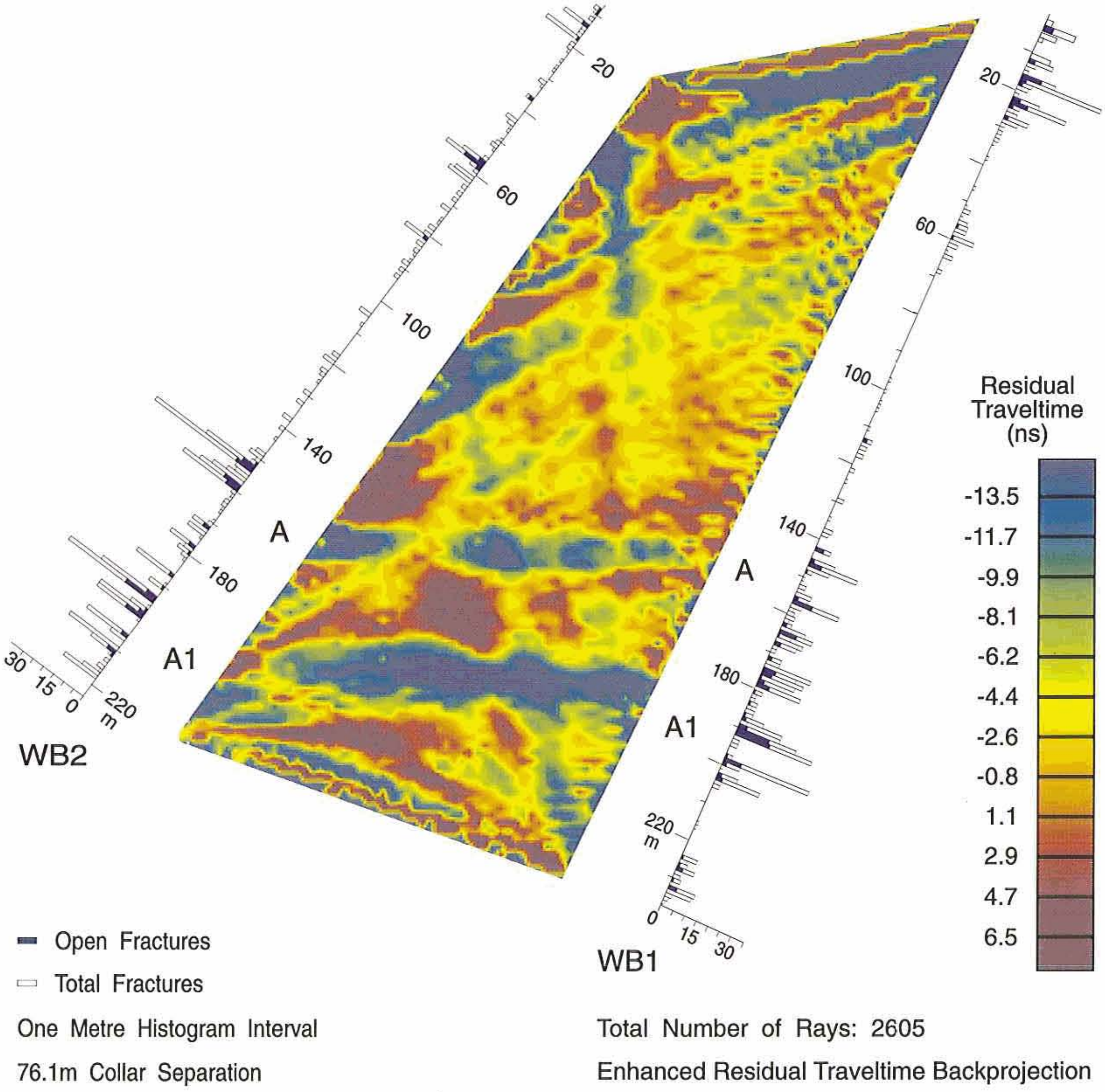


FIGURE 6-26: Cross-Hole Radar Tomogram, Boreholes WB1 and WB2

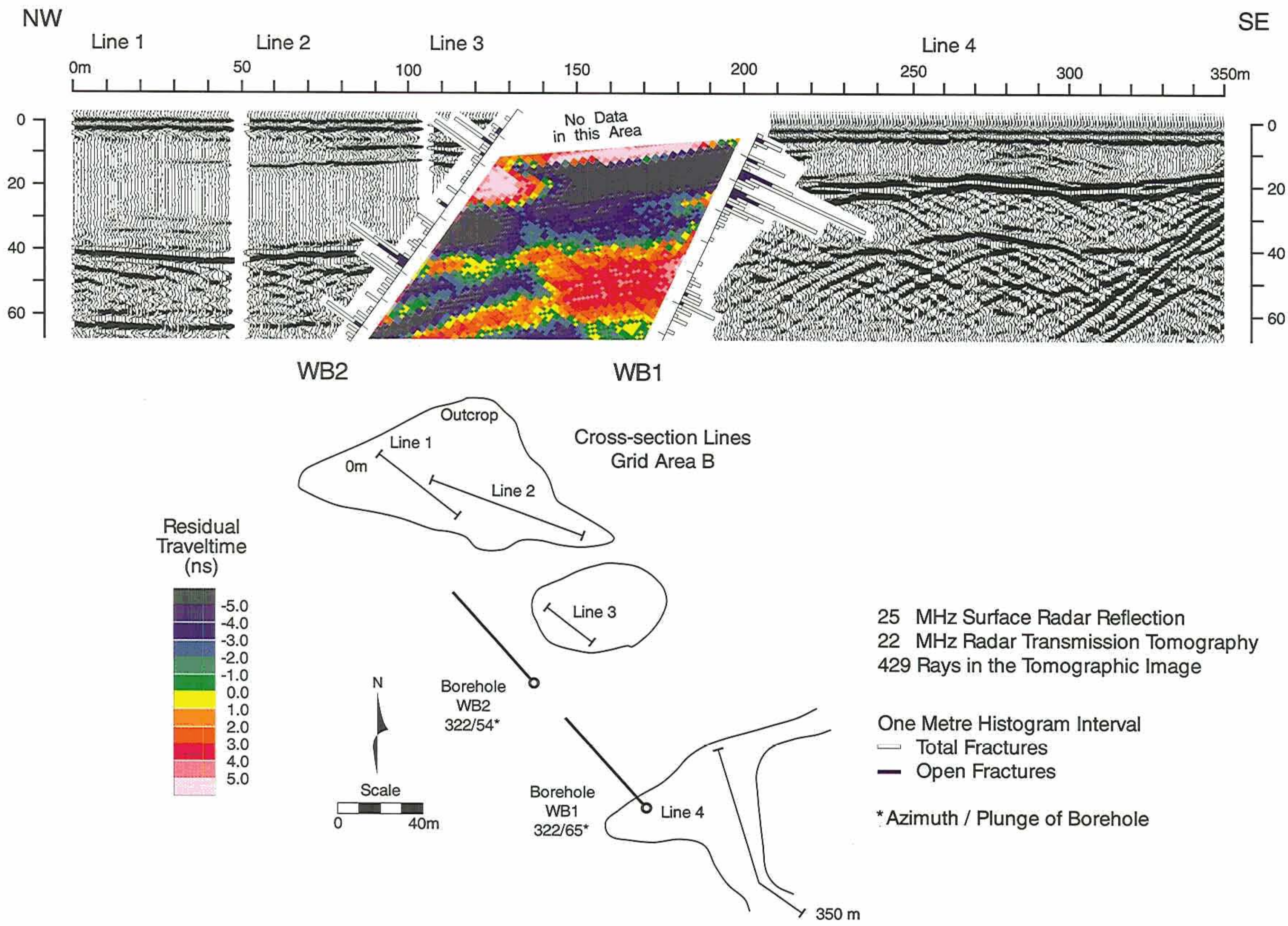


FIGURE 6-27: Integrated Cross-Hole Radar and Surface Radar Surveys at Grid Area B

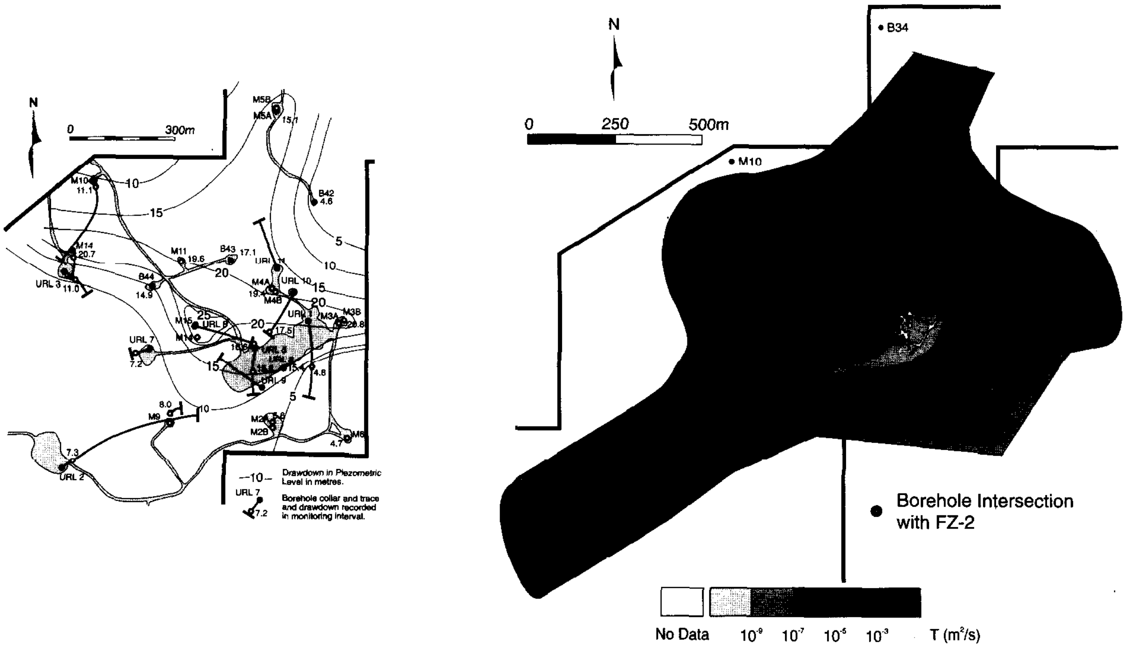
at deeper depths are in the range of 5700 to 5900 m/s. The low velocities of 5400 to 5600 m/s correlate with the regions of most concentrated fracturing between these boreholes at depths of 150 to 220 m and 280 to 310 m respectively. Cross-hole hydraulic interference tests were performed in these boreholes and have confirmed that hydraulic continuity exists along the two fracture zones (A and B, Figure 6.25) as mapped by the seismic tomography survey. Multiple borehole and cross-hole hydraulic tests are discussed later in Section 6.3.2.

Cross-hole Radar Tomography

Cross-hole radar surveys, similar to cross-hole seismic surveys, can be done by moving radar transmitters and receivers to numerous locations in two adjacent boreholes located within about 100 m of each other. Data are recorded for a number of survey fans. Each fan is generated by keeping the transmitter fixed at one position and moving the receiver to a series of different locations in the other borehole. The recorded signal is analysed with respect to the travel time and amplitude of the first arrival.

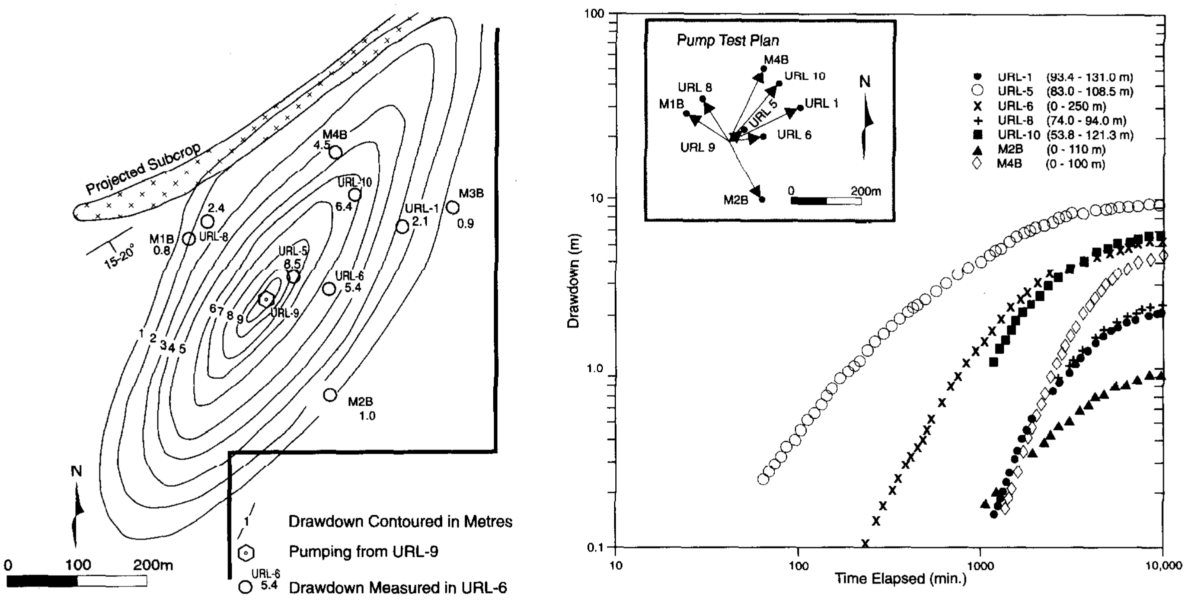
The results of cross-hole radar tomography, performed at a frequency of 22 MHz between the same pair of boreholes as used in the previous seismic tomography example, are shown in Figure 6.26. This survey was carried out in much greater detail than the seismic survey, since the radar transmitter and receiver were moved in steps of only 2 m. In the previous example seismic survey, the transmitter and receiver were moved in steps of 20 to 50 m. The radar residual travel time tomography shows the continuity of fracture zones A and A1 between these two boreholes. The slower radar velocity along fracture zone A1 at 210 m in WB2 to 200 m in WB1 suggests a greater degree of fracturing and potentially a higher permeability in the zone at this location (Figure 6.26).

In cases where rock outcrops are located near closely-spaced pairs of boreholes at the grid areas, surface radar survey methods and cross-hole 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. An example of this, also from grid area B, at the Whiteshell Research Area is shown in Figure 6.27. Cross-hole radar tomography data for the upper 70 m of boreholes WB1 and WB2 were processed to produce a residual travel-time tomogram for comparison with data from surface radar surveys. The zones of negative residual travel time on the cross-hole tomogram indicate zones of slowed radar wave propagation. These probably correspond to the locations of intense fracturing. These zones would also be expected to be potential pathways for groundwater flow between the boreholes. The fracture logs for the two boreholes show that open fractures occur where these zones are intersected by the boreholes (Figure 6.27). The results of the surface radar surveys from rock outcrops adjacent to the boreholes also show that these fracture zones can be traced for distances of up to 150 m away from the boreholes (Figure 6.27).



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



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 6-28: Examples of Multiple Borehole Hydraulic Interference Tests at the Underground Research Laboratory and a Long-Term Pump Test at URL-9

6.3.2 Multiple Borehole Hydrogeologic Tests

After the semi-permanent M-P casing systems are installed in the boreholes, hydrogeologic tests would be performed between multiple boreholes to assess the hydrogeological characteristics of large volumes of the rock surrounding, and between, the boreholes. These tests would be done by raising or lowering the groundwater pressure in an interval in one borehole while the groundwater pressure response is monitored in intervals in other surrounding boreholes. Usually this is done by either withdrawing (pumping) or injecting water into the zone. These hydraulic interference tests are one of the primary methods of developing an understanding of the permeability conditions between clusters of boreholes at a single grid area or site and between boreholes at adjacent grid areas.

As each borehole drilled at the grid areas of a candidate area or candidate site, was fitted with a multiple-interval M-P casing system, groundwater pressure levels in particular fracture zones (isolated by packers) could be monitored during the subsequent drilling of all additional boreholes. As shown during the initial subsurface characterization of the URL lease area, monitoring and interpreting the groundwater pressure responses recorded in adjacent boreholes during borehole drilling can provide 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 can be done in a particular borehole test zone while selected isolated zones in adjacent boreholes are monitored. These data can be used to determine the extent, groundwater storage and permeability of the fracture zones. The data can also be used to indicate the permeability and groundwater storage characteristics of the rocks adjacent to or between the fracture zones. For instance, the results of multiple borehole hydrogeologic tests performed within the large fracture zones at the URL lease area were used to determine both the interconnectivity and spatial variability of permeability within the 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. Figure 6.28 illustrates examples of some hydraulic interference tests performed in two of the large fracture zones at the URL and shows interpretations of the permeability distribution that can be drawn from such information.

The volume of rock that can be evaluated by multiple borehole hydrogeologic tests depends on a number of factors. These include the permeability and groundwater storage characteristics of the rock and the size and duration of the groundwater pressure disturbance that is created during the test. However, information has been obtained from these types of tests at the URL site to characterize the hydrogeologic properties of regions of the rock mass located up to 1 km radially away from the pumping or injection borehole.

6.3.3 Multiple Borehole Groundwater Tracer Tests

Fracture zone porosity, permeability and dispersion characteristics can also be determined by performing and analyzing multiple-borehole groundwater tracer tests. For instance a series of two-well groundwater tracer tests have been used 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, Davison et al. 1993). The results of these tests have revealed that porous media equivalent transport models can be used to simulate the tracer transport through large fracture zones, provided they properly account for the spatial variability that can exist in these properties within the fracture zones. These tests also indicate that as the transport distance increases in the fracture zones the effects 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 of rock that is usually evaluated by multiple-borehole tracer tests is relatively small (boreholes located up to a few hundred metres apart) in comparison to the size scale of interest for developing a groundwater flow and solute transport model of the candidate area. However, the information from tracer tests can assist in understanding the spatial variability that exists in the solute transport properties of the major fracture zones. In addition future tracer tests may be performed in fractured plutonic rocks over considerably larger distances than those performed so far. For instance we plan to perform multiple-borehole groundwater tracer tests over distance scales of up to 500 m within the large fracture zones at the URL lease area by 1995.

6.4 SYNTHESIS OF GRID AREA STUDIES OF REGIONAL AREA

Synthesis of the results of all the surveys and borehole investigations at the grid areas provides the basis for developing an understanding of the large scale groundwater flow systems of the candidate area. This understanding would be used to develop a conceptual model of the regional groundwater flow conditions for the area. The conceptual model would then be represented by a detailed three-dimensional mathematical description. The mathematical model of the groundwater flow system would be calibrated with 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 ahead of time the hydraulic responses to expect during particular multiple-borehole hydrogeologic tests and comparing these predictions to the observed responses.

Other solute transport aspects such as dispersion can be incorporated into the model and calibrated against the information obtained from multiple borehole groundwater tracer experiments at the site, albeit usually over shorter distance scales than the hydraulic tests. Once developed and calibrated, using all the available surface and subsurface data from the grid area studies, this model of the regional solute transport conditions would be used to evaluate and compare various options for locating a disposal vault. Such a model would assist in preparing preliminary safety assessments of the options for alternative site locations. A thorough discussion of the groundwater flow model development aspects and the transfer of the flow model into an assessment model that represents the entire disposal system is contained in Davison et al. (1994).

AECL recently began integrating all the information obtained from grid area investigations of the Whiteshell Research Area since 1985. The information is currently being assembled to develop and calibrate a large scale groundwater flow model of the research area. This model will cover an area of about 500 km^2 and will extend to a depth of about 1.5 km. This example will be documented during 1994. It will be an additional illustration of the proposed methodology for developing such large scale groundwater flow models in plutonic rocks of the Canadian Shield. This calibrated regional groundwater flow model of the Whiteshell Research Area will be used to show how an understanding of the large scale groundwater flow conditions of plutonic rocks and their surroundings can assist in evaluating alternative locations for a nuclear fuel waste disposal vault within the hydrogeological setting of a candidate area. Such a regional evaluation of groundwater flow conditions, using field and modelling methods, would be an important component of the process of selecting a suitable location for the disposal vault at a candidate area.

7. SURFACE-BASED EVALUATION OF A CANDIDATE SITE FOR A DISPOSAL VAULT

7.1 INTRODUCTION

After consideration has been given to various alternative locations within the larger regional context of the geologic, hydrogeologic and environmental setting of the candidate area, a candidate site would be identified for the disposal vault. The emphasis of site evaluation would shift then to a smaller geographic area (the candidate site) comprising an area of perhaps 25 km^2. Intensive surface-based site evaluation studies would be conducted at the candidate site with the primary objectives of selecting and confirming the suitability of the location for the underground vault and, to identify locations for exploratory shafts and tunnels.

The site evaluation work at the candidate site would be closely integrated with performance assessment studies and disposal vault design studies. These studies would be iterative. For instance, the layout of underground rooms and tunnels might be modified as more detailed site characterization information was collected. Also, performance assessment analyses based on the detailed site information might suggest that certain design constraints would be required to meet regulatory standards. The analysis might indicate areas of the site where more detailed characterization was required, particularly if the analysis

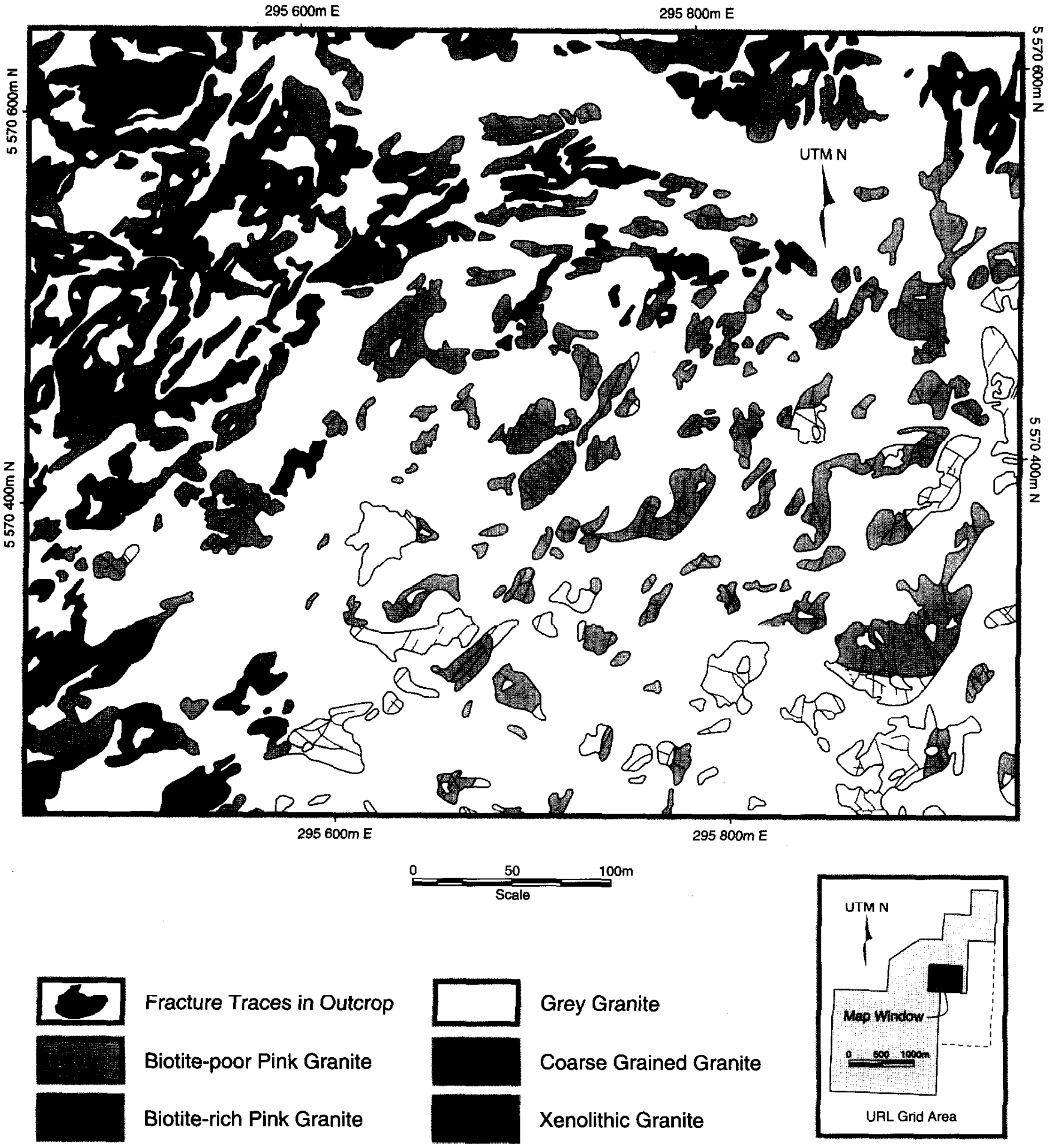


FIGURE 7-1: Geologic Map of the North Central Portion of the Underground Research Laboratory Lease Area

revealed that a particular feature represented a potentially significant constraint on the design and performance of the disposal vault.

The surface-based characterization activities for evaluating the candidate site, including those areas where a particularly detailed characterization was needed, would be the same as the activities used to investigate the grid areas for evaluating the candidate area (Chapter 6). The surface-based evaluation of a candidate site would conclude with the selection of locations for constructing exploratory shafts and tunnels and the establishment of a monitoring system surrounding these locations. The monitoring system would record the mechanical and hydraulic perturbations created by the excavations. These perturbations would be compared with predictions made by models that simulate the expected disturbances.

7.2 SURFACE-BASED CHARACTERIZATION OF THE UNDERGROUND RESEARCH LABORATORY SITE: A CASE STUDY EXAMPLE

The siting and construction of the Underground Research Laboratory (URL) has provided an excellent example of site characterization, development and calibration of geologic and hydrogeologic models, model predictions and verification. Although the URL lease area is much smaller than a site for a disposal vault would be, (~5 km^2 for the URL lease versus ~25 km^2 for a candidate disposal vault site) and the depth of subsurface investigation was mostly limited to about 500 m at the URL (versus depths of 1 km or greater at a candidate disposal vault site), virtually all the geotechnical aspects of surface-based site characterization that we would expect to be used at an actual candidate disposal vault site have been applied and tested at the URL lease area.

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-based geophysical surveys; drilling, sampling, and instrumentation of a series of shallow boreholes into the overburden deposits; and, installation of surface water and meteorological monitoring instrumentation.

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 represent the roof and core zones, respectively, of the granitic Lac du Bonnet Batholith (Stone et al 1984; Brown et al. 1984; Brown et al. 1985). The pink granite contains numerous fractures. Most of these are subvertical and oriented in a NNE-SSW direction. The grey granite is uniform and virtually free of subvertical fractures at surface (Figure 7.1).

Several surface geophysical conductors were identified by the VLF-EM tilt angle method (Soonawala 1994a). Figure 7.2 shows the locations of these conductors on the URL lease. Drilling confirmed that the conductor labelled AA′ corresponds to the intersection of a major low-dipping fracture zone with groundsurface. Many of the other conductors shown on Figure 7.2 may be similar zones of fracturing in the rock body, although drilling has not been performed to confirm this.

The surface distributions of fractured pink granite, unfractured grey granite and xenolithic granite were mapped at the URL lease area and these were traced to some extent by magnetic and gradient-configuration resistivity methods (Soonawala 1994a).

The depth and distribution of the overburden deposits at the URL lease area were determined by the VLF-EM resistivity technique (see Figure 7.3) and Schlumberger resistivity soundings also produced satisfactory estimates of overburden thickness at particular locations (Soonawala 1994a).

The areal continuity and structure of one major low dipping fracture zone in the rock mass was indicated by seismic reflection surveys done from the surface of the URL lease area (Soonawala 1994a). Figure 7.4 shows the interpretation of the seismic reflection data. The depth of this fracture zone has been determined at many locations in drillholes, and the depth accuracy of the interpretation of the seismic data has been found to be poor when compared to the depths from the drillhole data, but the seismic data qualitatively indicates the general dip of the fracture zone, and is useful. The interpretation of the seismic data also indicated the existence of additional fracture zones in the rock that were not encountered in the boreholes.

In summary, the following surface geophysical survey methods proved useful in characterizing various aspects of the surface and subsurface geological conditions of the URL lease area (Soonawala 1994a): VLF-EM tilt angle, VLF-EM resistivity, magnetic, gradient-configuration resistivity and Schlumberger resistivity. Seismic reflection surveys showed some potential to identify low-dipping fracture zones as reflectors to depths of 500 m although the interpretation of the data was ambiguous. In general, because of the distribution of highly conductive overburden materials at the URL site, most electrical-based geophysical methods were unable to identify lithologic or structural heterogeneities in the rock. Therefore useful results were not obtained at the URL lease area from the magnetotelluric, magnetometric resistivity and most moving-electrode resistivity methods. These methods might be more useful at sites with less conductive overburden.

The surface-based characterization of the URL lease area initially involved drilling five deep, cored boreholes to check the interpretation of site conditions that was 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 due to a secondary alteration of the granite minerals by fluids moving through the fractures (Brown et al. 1984). Figure 7.5 is a schematic diagram that was developed from the borehole information to depict the relationships between the various granite phases and the alteration episodes that affected the Lac du Bonnet Batholith (after Brown et al. 1985).

Moderately fractured pink granite occurred primarily in the upper 100 m of the rock mass at the URL site with the fracture density highest

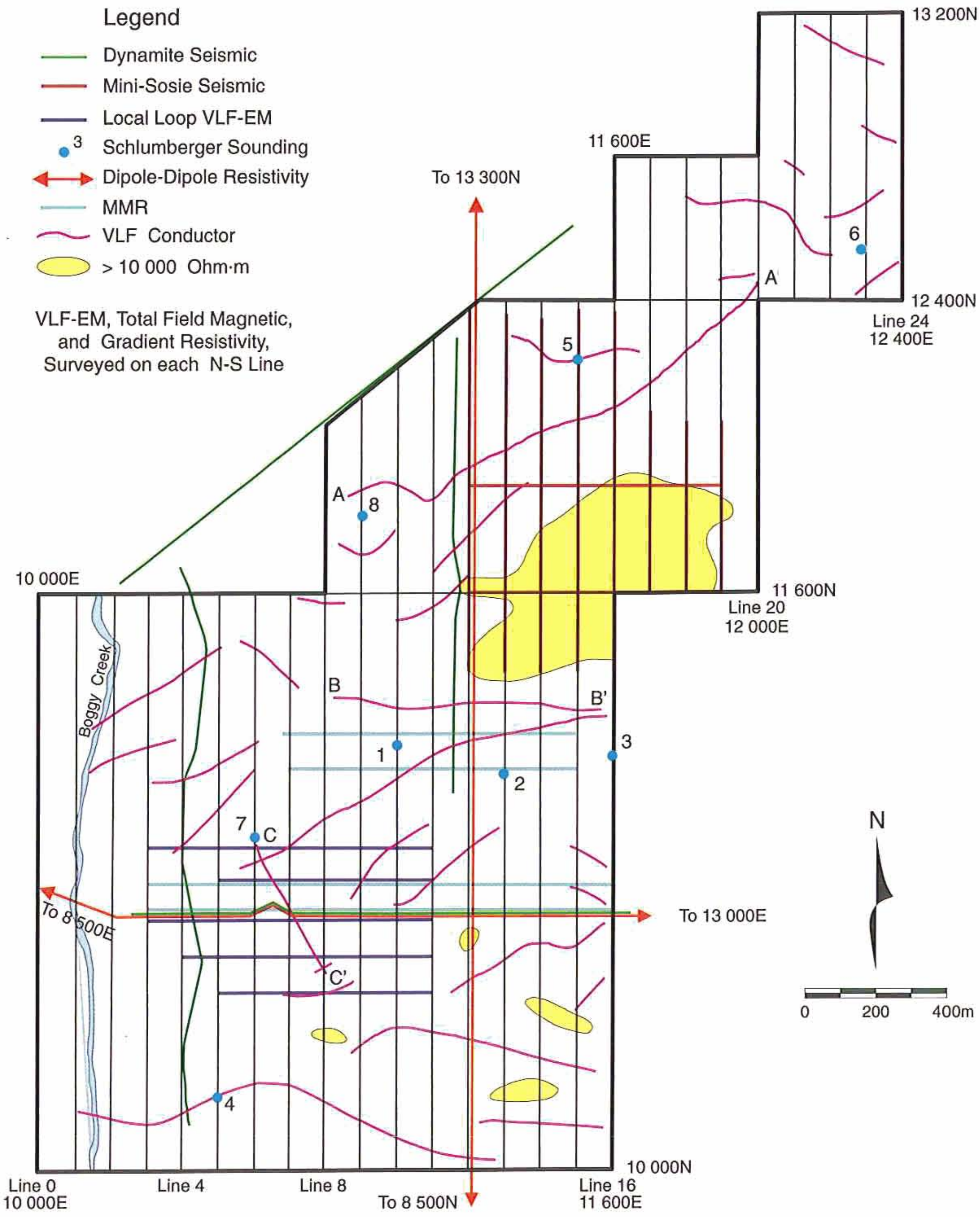


FIGURE 7-2: VLF-EM Conductors and Resistivity Zones in the Underground Research Laboratory Lease Area

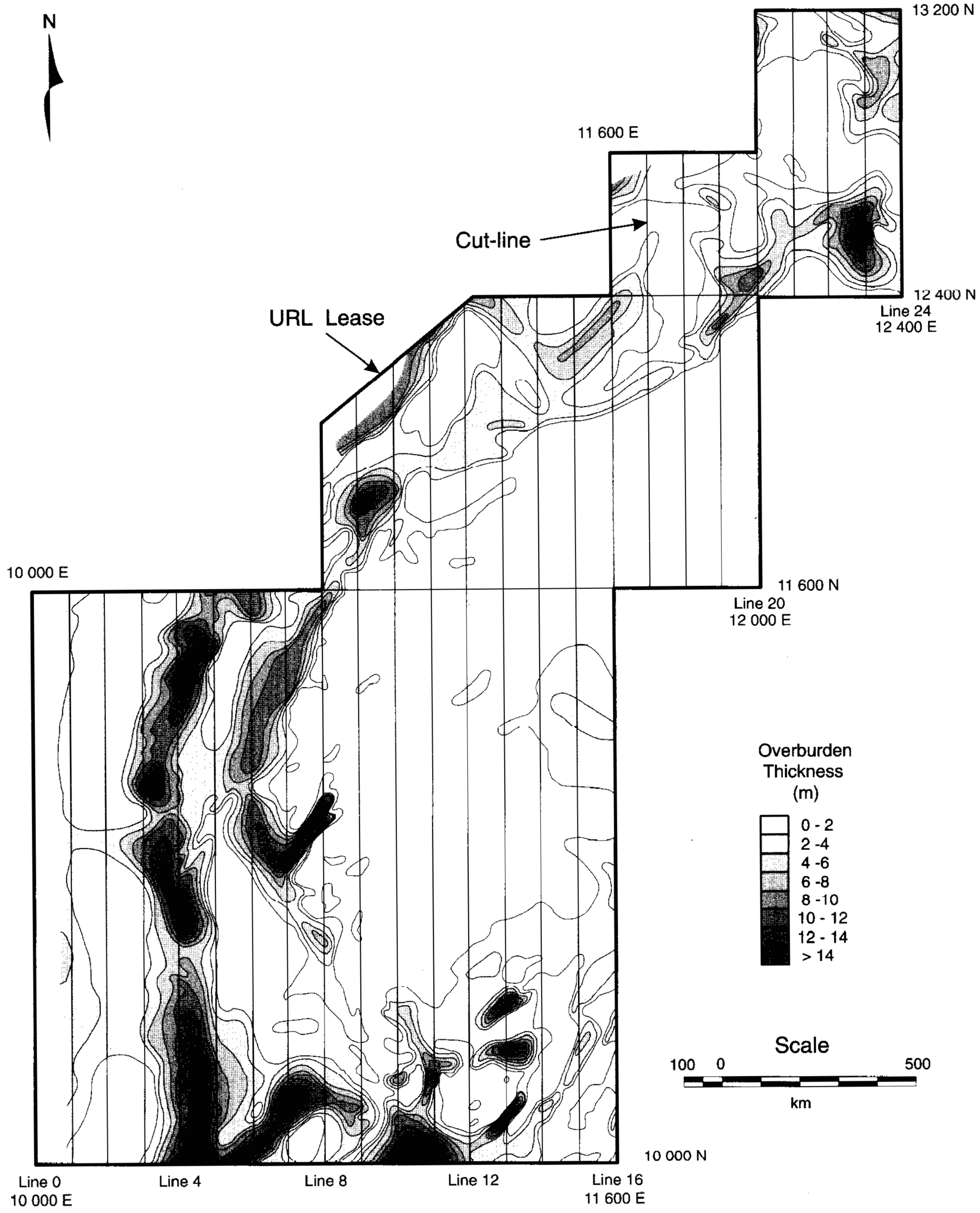


FIGURE 7-3: Overburden Thickness Map of the Underground Research Laboratory Lease as Determined from VLF Resistivity

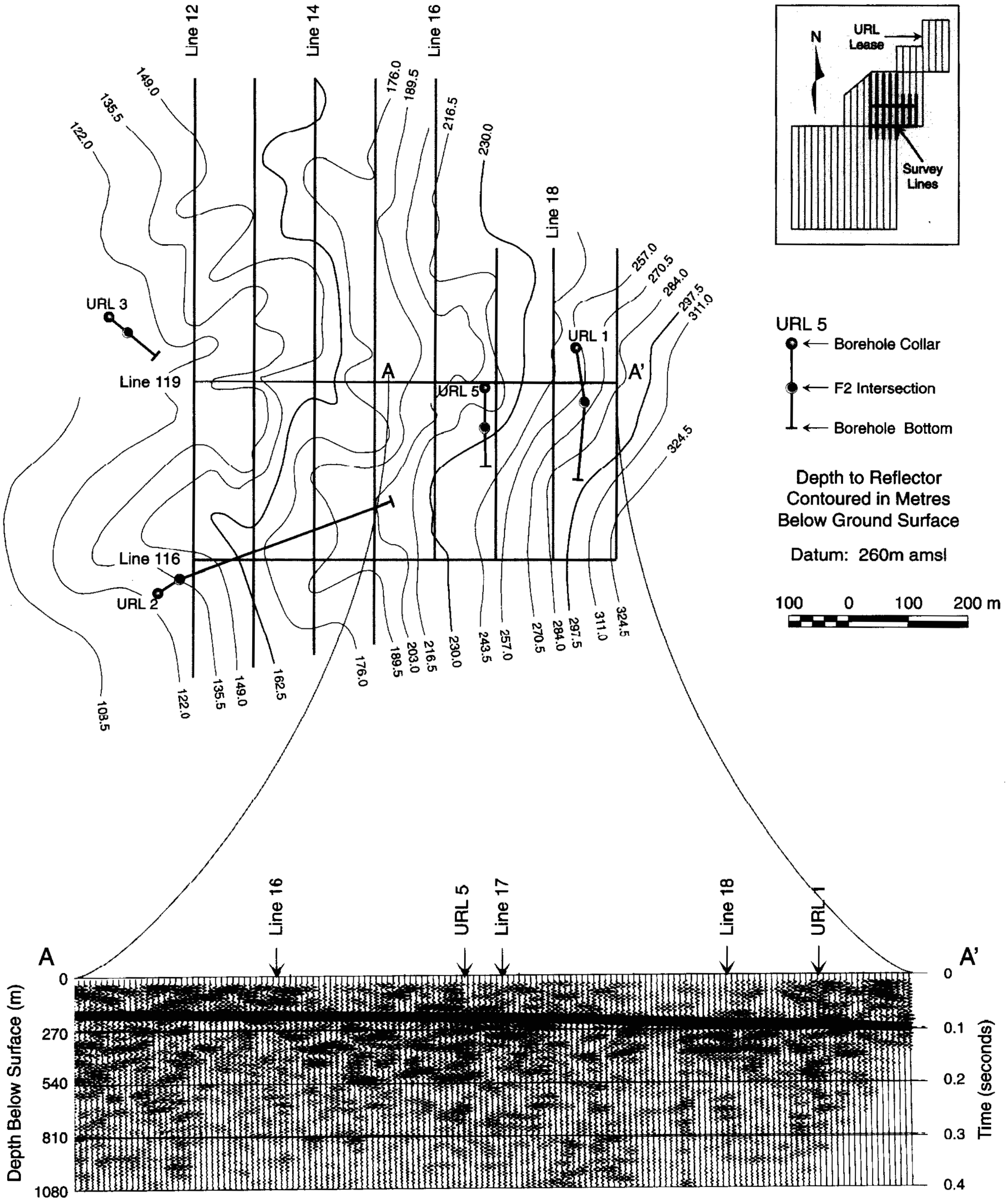


FIGURE 7-4: Depth to Fracture Zone 2 at the Underground Research Laboratory from a Seismic Survey

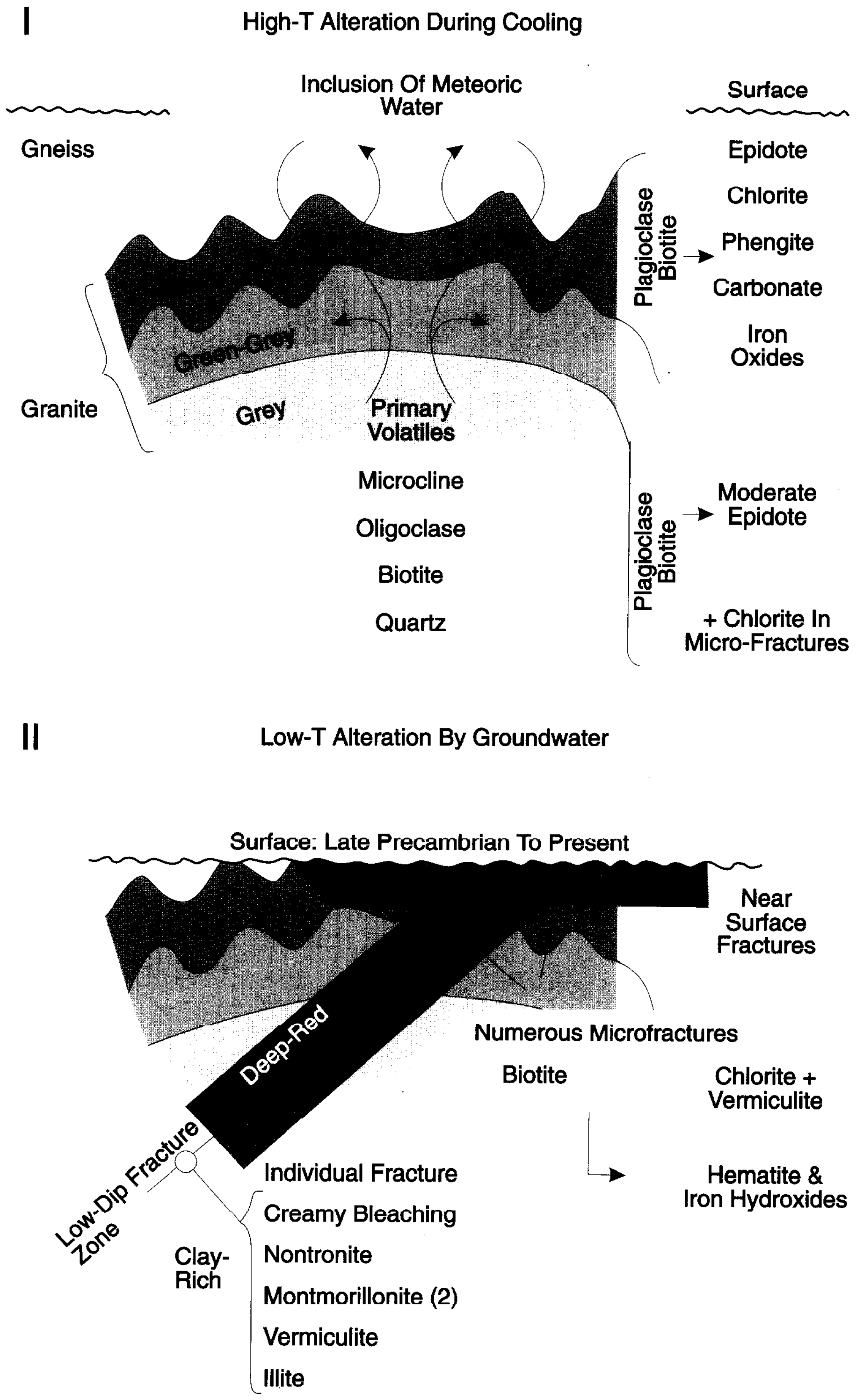


FIGURE 7-5: Relationships Between Granite Phases and Alteration Sequences

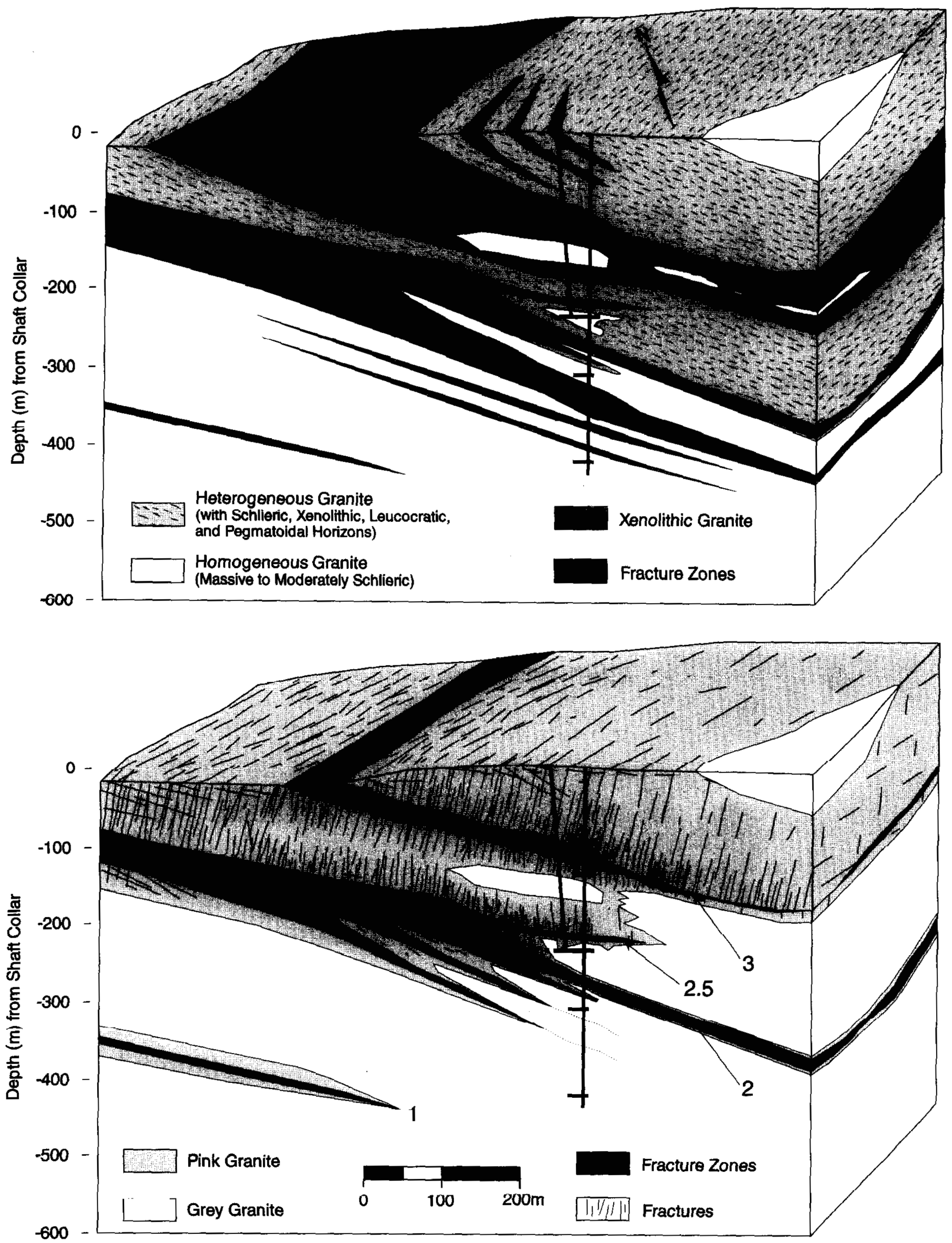


FIGURE 7-6: Block Diagram Illustrating the Geology at the Underground Research Laboratory

between 50 and 100 m. Pink alteration occurred along discrete fractures and also in association with extensive low-dipping zones of intense fracturing cutting through both the pink and grey granite. These fracture zones exhibited reverse dip-slip fault movement with lenticular gouge zones. They were partly altered to clay and contained groundwater with relatively high salinity, particularly at depth. The subsurface investigations carried out in the initial deep 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, and 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. Sparsely fractured rock occurred below 270 m depth.

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

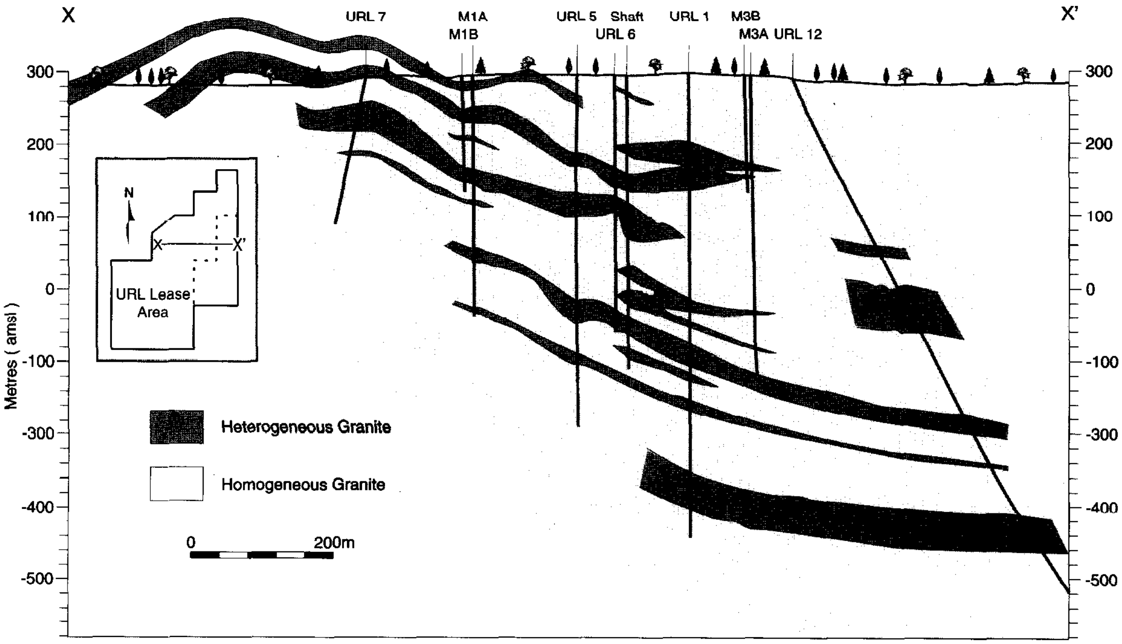


FIGURE 7-7: Geologic Section Showing Antiform Fold Structure in the Underground Research Laboratory Lease Area

The information from the additional boreholes revealed that the location and geometric orientation of the major low-dipping fracture zones in the rock mass at the URL site were strongly controlled by a large scale layering of schlieric and xenolithic granite in the batholith (Figure 7.6). The schlieric banding identified in the boreholes also confirmed that the URL lease area was underlain by an antiform fold structure in the batholith (Figure 7.7). The extra borehole data showed that portions of the low-dipping fracture zone at 270 m near the shaft location were slightly shallower than expected. The design of the underground tunnel layout for the 240 m depth level was modified to avoid intersecting this zone (Brown et al. 1984).

Extensive hydrogeological testing was done in the network of deep boreholes. Hydraulic responses were monitored in packer-isolated intervals in existing boreholes as new holes were drilled at the site. 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 in the rock at the URL lease area. Three extensive, shallow dipping fracture zones were found to control most of the groundwater flow through the rock mass at the URL lease area (Figure 7.8, Davison 1984b). The groundwater flow was confined mostly to these major fracture zones. There was very little hydrologic connection between the major fracture zones, however, some minor hydrologic interconnections were evident along the trend of some topographic lineaments. These lineaments were inferred to be permeable, subvertical fracture zones (Davison 1984b).

After the URL site was characterized using the surface-based methods, but before any construction of the shafts or tunnels of the URL facility began, the data was used for a major experiment to evaluate groundwater flow models. 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 by mathematical models which simulated the hydrogeology of the URL site (Betcher and Pearson 1982).

Several modelling teams participated in the study initially, but only two of the teams produced predictions of the hydrogeologic disturbance that would be created by the excavation of the URL shaft (Guvanasen et al. 1985). The INTERA modelling team used a finite difference code (SWIFT) to simulate the hydrogeological conditions whereas the AECL modelling team used a finite-element code (MOTIF). Both teams used the hydrogeologic data provided by the surface-based site evaluation program to develop and calibrate their models. The data from multiple-borehole hydraulic interference tests and piezometric pressure records were particularly useful in the model calibrations (Guvanasen 1984, INTERA Technologies 1985, Guvanasen et al. 1985). The MOTIF code was developed specifically to model groundwater flow in fractured rock. MOTIF incorporated discrete planar elements to represent the major fracture zones. These planar elements were superposed on a volume-element mesh representing the remainder of the rock mass as an equivalent anisotropic porous medium with three-dimensional permeability, porosity, and

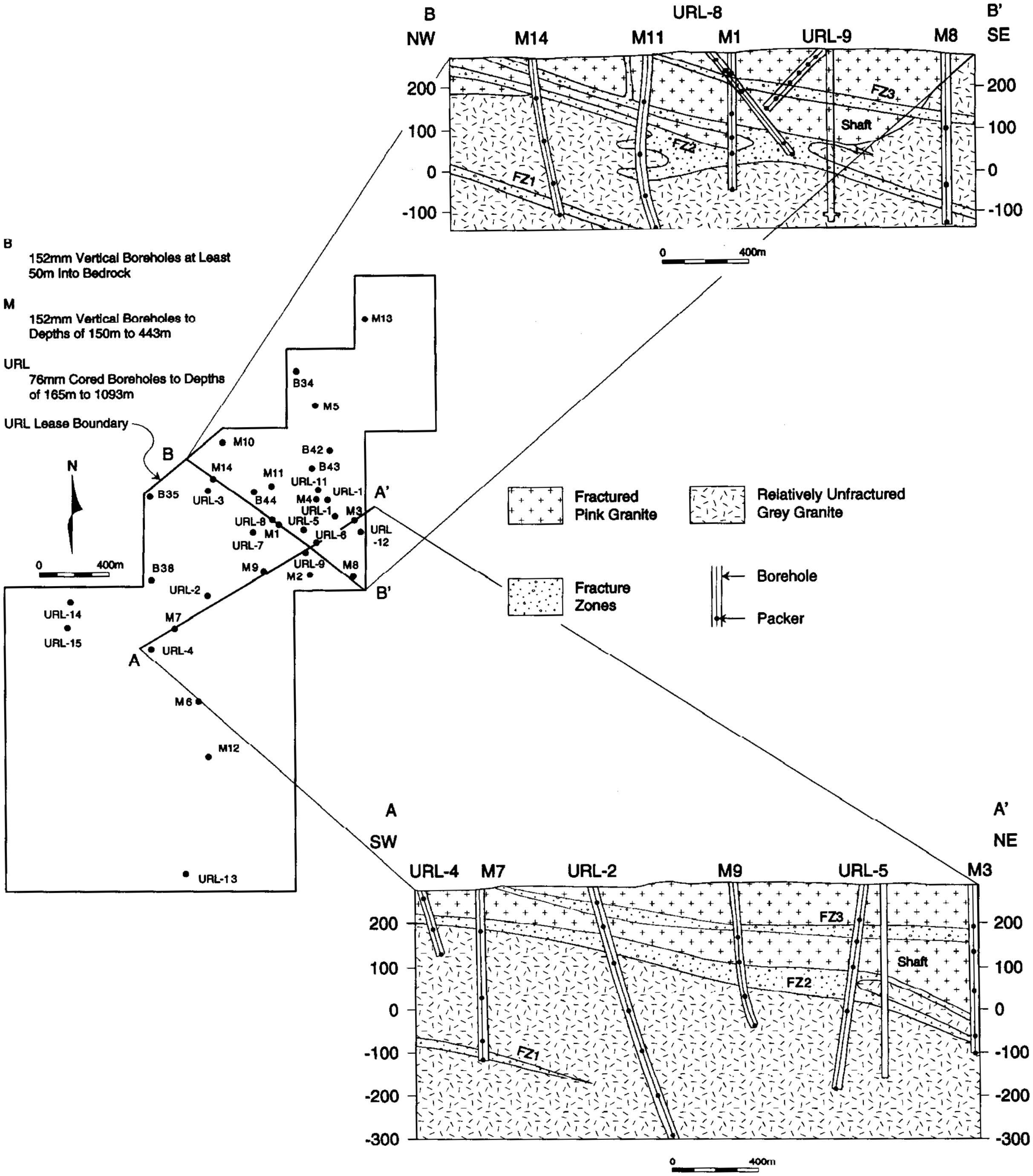


FIGURE 7-8: Hydrogeologic Cross-Sections Through the Underground Research Laboratory Lease Area

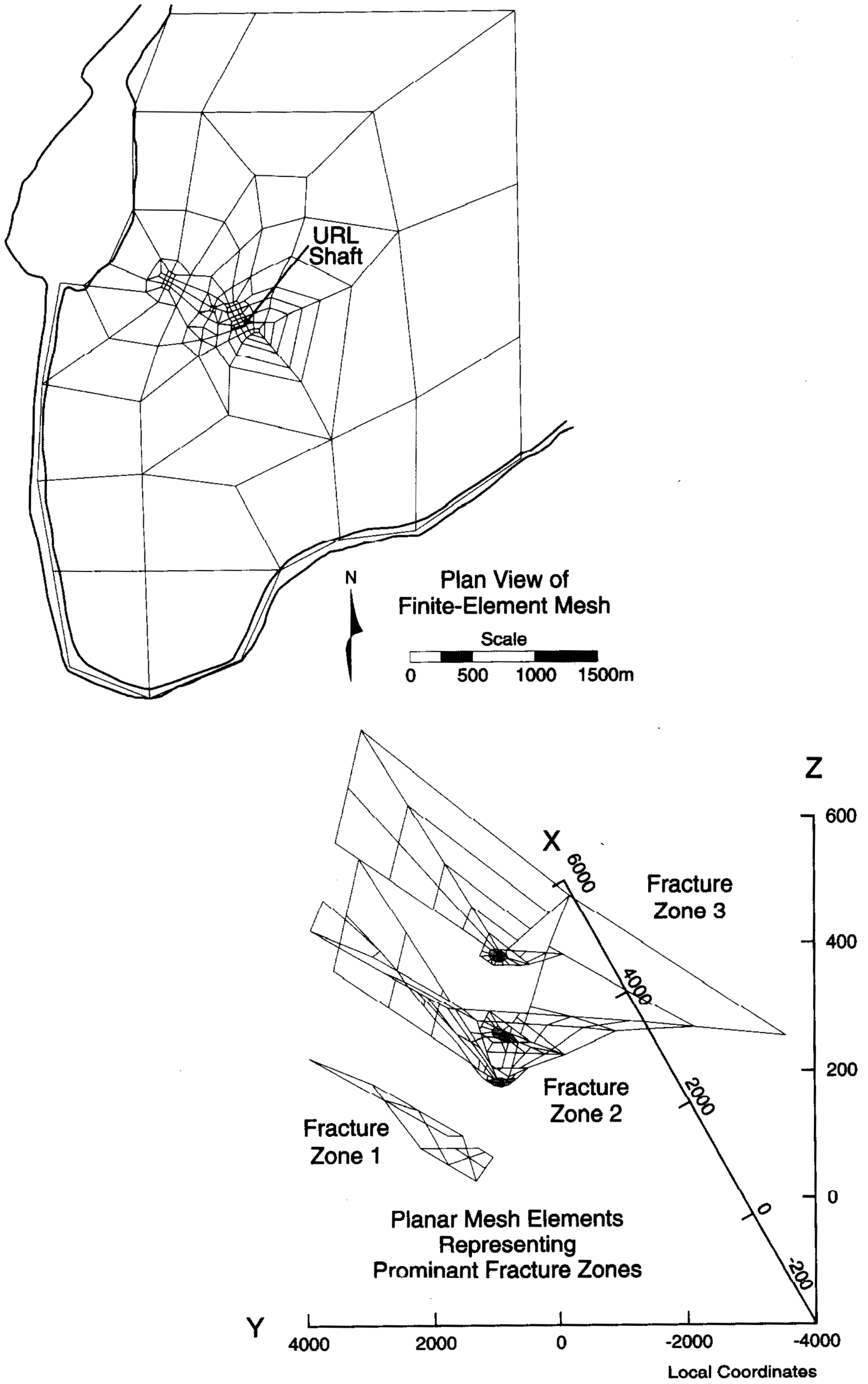


FIGURE 7-9: MOTIF Finite-Element Grid of the Hydrogeology of the Underground Research Laboratory Lease Area

dispersivity characteristics (Guvanasen, 1984, Davison and Guvanasen 1985). The permeability and porosity characteristics were varied spatially along the planar elements to represent known heterogeneities such as channels of high permeability or regions of low permeability within the fracture zones. The properties of the volume elements were varied to represent the distribution and orientation of fractures in the remainder of the rock mass. Figure 7.9 shows how the geological features at the URL site were represented in AECL's hydrogeologic model of the URL site.

A larger regional groundwater flow model of the area surrounding the URL lease was also constructed. It was initially calibrated by adjusting groundwater infiltration rates until surface hydraulic heads corresponded to the water table topography. Then, sensitivity analysis was done with this model to establish the hydrogeologic boundary conditions for a more detailed local model describing the groundwater flow conditions of the area surrounding the URL lease. This local model focussed on the location chosen for the URL shaft.

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 properties were then calibrated by adjusting the values of the hydraulic parameters within the fracture zones and rock mass regions of the model until there was good agreement between calculated and measured steady state piezometric pressure values. Further calibration was done by ensuring the calculated transient piezometric responses were similar to field measurements made during the various large scale groundwater pumping tests at the URL site. Following this final stage of calibration, the hydrogeologic model was used to predict the groundwater pressure responses at 171 locations in the surrounding rock mass due 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 in the rock mass where actual measurements of the pressure response could be made. 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 continuously at the URL site since shaft sinking began in May, 1984 and these allow a comprehensive comparison with the predicted responses. The results of the comparison show that the predictions of groundwater pressure response made by AECL using the MOTIF code were somewhat better than the predictions made by INTERA using the SWIFT code (Kozak et al. 1994). Generally, the MOTIF model slightly overestimated groundwater inflow rates to the shaft but agreed well with the trend of flow rate with time. The spatial and temporal pattern of the groundwater pressure responses within the variably fractured rock mass and within the major fracture zones were also predicted very well by the MOTIF model. Figure 7.10 illustrates some examples of the groundwater pressure responses predicted by the MOTIF model compared to the observed responses (after Davison 1986).

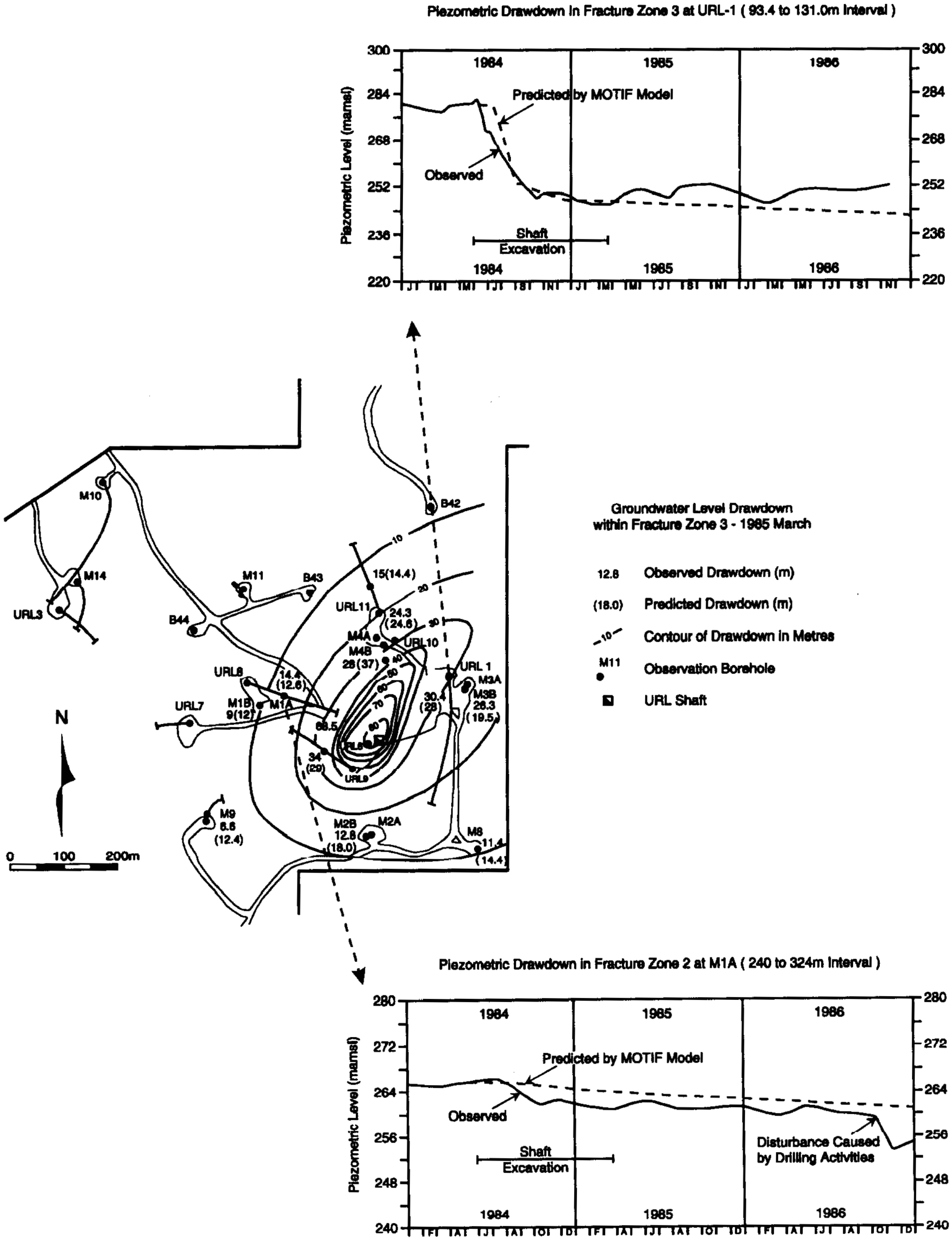


FIGURE 7-10: Comparison Between Predicted and Observed Piezometric Response from the Underground Research Laboratory Drawdown Experiment

The monitoring of the hydrogeological response around the URL excavations will continue until the underground facilities are closed. This ongoing monitoring will provide additional insight into groundwater flow in fractured plutonic rock. The monitoring will also provide information about the long term reliability of groundwater monitoring equipment such as packers and MP casing systems.

The results of the modelling and monitoring of the disturbance caused by initial shaft sinking at the URL have given us confidence in our ability to incorporate field data into models that are adequate representations of groundwater flow in fractured plutonic rock. The results support the conceptual groundwater flow model that was developed for the URL site from the site characterization information before any underground shaft construction began. The results also support the numerical approach and calibration procedure used to mathematically describe the hydraulic aspects of the groundwater flow system at the URL site. The study demonstrated the applicability of using the porous media equivalent approach to describe the hydraulic properties of the fractured rock mass, in particular the importance of using planar elements to describe the location, geometry and spatial variability of the hydraulic properties of the major fracture zones. This experiment was an important demonstration of many of the detailed site evaluation methods that would be used to characterize and model groundwater flow conditions at a plutonic rock site for nuclear fuel waste disposal.

The conceptual model used to develop the groundwater flow model and the geosphere model for the postclosure assessment case study for our disposal concept is based on the field information from the Whiteshell Research Area (Davison et al. 1994). In the vicinity of the URL, the model is essentially the same as the conceptual model that was used to develop the MOTIF groundwater flow model that successfully predicted the drawdown caused by constructing the URL shaft. The geosphere model used for the postclosure assessment case study represents the level of detail that would be expected to be available for an initial assessment at a potential disposal site during site evaluation (before exploratory excavation). However, the area characterized at the URL site (about 4 km^2) is considerably smaller than what would be required for a potential disposal site (about 25 km^2 in size) or for identifying a preferred vault location within a candidate area (about 400 km^2 in size). We are currently revising and calibrating the conceptual model of groundwater flow at the Whiteshell Research Area to take account of additional information from continued characterization of the underground excavations of the URL and from our investigations of regional groundwater flow at the Whiteshell Research Area (about 450 km^2 in size). This will illustrate how a model of groundwater flow conditions at a candidate area could be used to identify a candidate site for a preferred vault location.

8. UNDERGROUND CHARACTERIZATION OF THE CANDIDATE DISPOSAL VAULT SITE DURING EXPLORATORY EXCAVATION

8.1 INTRODUCTION

The objectives of constructing and characterizing exploratory underground excavations at the candidate site for the disposal vault are threefold:

- to confirm the suitability of the site for a disposal vault,
- to provide site specific information needed to design a suitable layout for the waste emplacement panels and rooms and the other underground facilities of the disposal vault, and
- to demonstrate the suitability of the site in an Environmental Impact Statement which would be required to support an application for a license to construct the disposal vault.

As with the previous surface-based site evaluation studies, the application of the underground characterization program during exploratory excavation would follow an iterative, observational approach. This would ensure that the progressive refinement in the understanding of site conditions, which would inevitably occur as exploratory excavation proceeds, would continually be incorporated into 1) the plans for subsequent characterization, and 2) the designs for underground excavations of the disposal vault.

Once the initial exploratory excavations were completed and the results of the underground characterization of these excavations had been assessed, a decision on whether to construct a disposal vault at the candidate site would have to be made. An iterative approach during the excavation of the exploratory shafts and tunnels would help in optimizing the vault design and would increase the likelyhood that all potentially important site-related issues would be identified early in the design process.

An important requirement of the site screening and evaluation approach, outlined in this report, is that the process should demonstrate that the understanding of the geological, geomechanical and hydrogeologic conditions of the site developed by characterization is valid. One such demonstration would be the last component of the site evaluation performed during the siting stage. It would include three aspects:

- predicting the geologic and hydrogeologic conditions encountered by the exploratory shafts and tunnels,
- predicting the hydrogeologic and geomechanical responses in the rock mass to excavation of the exploratory shafts and tunnels at the site, and
- confirming these predictions.

During the surface-based evaluation of the candidate site selected for the disposal vault, locations would be chosen for exploratory shafts and tunnels. A hydrogeologic monitoring system would be installed in an array of boreholes in the volume of rock surrounding these locations and a hydrogeological model of the site would be developed and calibrated. This model would be used to predict the hydrological response to the construction of the exploratory excavations to be observed in the monitoring system. Other conceptual and numerical models would be used to predict the geologic conditions and geomechanical responses to be encountered by the excavations.

Characterization of the exploratory shafts and tunnels, during construction, and monitoring the mechanical and hydraulic responses in the rock surrounding the shaft and tunnel locations, will provide the data needed for comparison with the predictions made with the various models.

In addition to demonstrating how well the site was understood, this monitoring would provide new data to improve the models, as well as reduce the uncertainty in the parameter values used in the models. Furthermore, this underground characterization would provide the site specific data needed to finalize the design of the underground vault taking into account particular site features and characteristics. It would also define additional requirements for the characterization work that would be required during the subsequent construction and operation stages.

For instance, the vault design would require detailed information on in situ mechanical rock properties and the state of in situ stress. This information would need to be obtained from measurements made underground over a range of rock volumes to determine the dependence of the results on the scale of the measurement. Experience at the URL indicates that observations from large volumes of rock (excavation convergence, microseismic monitoring and cross-hole seismic surveys) which were carried out during the construction of exploratory excavations provide valuable information on the site specific variations in the state of stress (Martin 1990). Such information would be needed to make design decisions about the exact location and orientation of waste emplacement rooms for the disposal vault, and about the spacing and arrangement of emplacement boreholes if a borehole emplacement design were adopted. It would also be needed to design excavations to minimize excavation damage and to identify areas where engineered seals would be constructed.

Also critical to the design process are the locations of any fracture zones or faults which exist in or near the location chosen for the vault. Information would be needed regarding their size, orientation and solute transport properties. Waste emplacement rooms in the disposal vault would be located preferably in volumes of sparsely fractured rock between or away from such important groundwater pathways. The number of these volumes required for the layout of the waste emplacement rooms in disposal vault will depend on:

- the distribution and properties of the fracture zones,

- how the flow within the fracture zones was related to far-field, regional groundwater flow systems, and

- the groundwater flow and solute transport properties of the sparsely fractured rock volumes between the waste emplacement rooms and the fracture zones.

Depending on the particular conditions at the site, it might be necessary to specify a minimum distance between the waste emplacement rooms and the faults or fracture zones. If required, this would be an important site-specific design constraint. Determining if such a constraint was required and what it should be, would be a primary objective of the site characterization activities. This would require knowledge of the geometry and contaminant transport properties of the features controlling groundwater flow at the site. It would also require an evaluation of the potential for these conditions to be changed during the preclosure and postclosure periods. Much of this knowledge would be provided by the surface-based evaluation of the candidate disposal vault site. However, underground characterization in the exploratory shafts and tunnels would be needed to confirm that the understanding of site conditions was adequate.

Geophysical methods have been developed for scanning the rock adjacent to underground excavations to detect the presence of fractures and fracture zones. Ground penetrating radar and seismic reflection surveys have been used at the URL to detect fractures in the rock behind the shaft and tunnel walls. In addition, boreholes drilled from the shafts and tunnels would provide information on any fractures that might exist in the rock surrounding the excavations. These methods are described in the following sections.

Underground characterization in the exploratory shafts and tunnels would provide the first opportunity at the site to systematically record detailed data for a significant volume of rock. Consequently characterization should be done concurrently with the construction to allow sufficient access to collect the data and to install instrumentation for recording any time dependant phenomena.

The exploratory shafts and tunnels would also be used to investigate specific subsurface geological conditions, that were identified during the previous surface-based site evaluation, and would provide access for obtaining detailed information not obtainable from the previous investigations. This would require special construction procedures and schedules to maximize the amount of information obtained when the excavation intersected geological features or conditions of particular interest. For example, prior to excavation through a lithologic or hydrogeologic feature, the excavation could be stopped several tens of metres from the feature and hydrogeological/mechanical instrumentation could be installed to measure the conditions and monitor the response to excavation.

The design of all exploratory shafts and tunnels would need to take account of the special requirements of the underground characterization program. To simplify the understanding of insitu stresses, the exploratory excavations should have a circular cross section over the intervals where information was to be collected for detailed geotechnical analysis. We would expect the structural support requirements for the exploratory shaft to be minimal. Therefore there should not be a need for shaft liners or other support systems that would cover the excavation surfaces before they could be mapped and photographed.

The construction contract and the excavation methodology used for the exploratory excavations should be optimized to provide the underground characterization teams with as much time as necessary to conduct their investigations. On the basis of the experience gained in constructing the URL, this would likely require the negotiation of special contractual procedures and the fabrication of specialized underground equipment not usually used for mining or civil construction (Kuzyk et al. 1986; Peters et al. 1988). Such contracts and equipment would be necessary to provide the maximum flexibility to the underground characterization teams.

A wide range of methods would likely be used in the exploratory shafts and tunnels to characterize the rock mass and measure its response. These would include many methods similar to those described in the previous sections such as geological mapping, geophysical surveys, and hydrogeological testing and monitoring. However the methods would often be modified to accommodate their application in underground excavations. Additional methods unique to underground characterization would also be used to determine the in situ mechanical response of the rock mass particularly in the immediate vicinity of the excavations.

The technology necessary to implement the underground characterization activities is generally available. AECL developed and tested many of the methods during the excavation of the shafts and tunnels for the URL. The following section outlines the underground site characterization methods. A more complete discussion is given by Everitt et al. (1994).

8.2 UNDERGROUND CHARACTERIZATION OF EXPLORATORY SHAFTS

8.2.1 Continuous Characterization During Shaft Excavation

Many activities would be performed on a continuous basis during the excavation of the exploratory shafts. These would provide a continuous record of the variation with depth in rock lithology and structure and would measure time dependant variations. The activities would include:

- daily geologic mapping and stereophotography of the shaft walls and bottom;
- hydrogeological observations and the collection of groundwater samples at any groundwater seepage locations in the excavation walls;

- regular installation and recording of convergence pins to measure geomechanical responses; and
- conducting geophysical surveys of the shaft walls using radar and seismic methods.

The reports by Everitt and Brown (1986), Everitt and Hillary (1987), Stone and Kamineni (1988b), Everitt et al. (1990), and Everitt and Gann (1990) provide numerous examples of the underground geologic observations made during the sinking of the shaft at the URL. Figure 8.1 is a geologic map for a portion of the URL shaft which illustrates the type of geologic information that was gathered.

Figure 8.2 shows the type of information that was obtained in the URL shaft by performing ground penetrating radar surveys along the walls during construction (Holloway et al. 1986). Individual water saturated fractures were traced for several metres behind the excavation walls

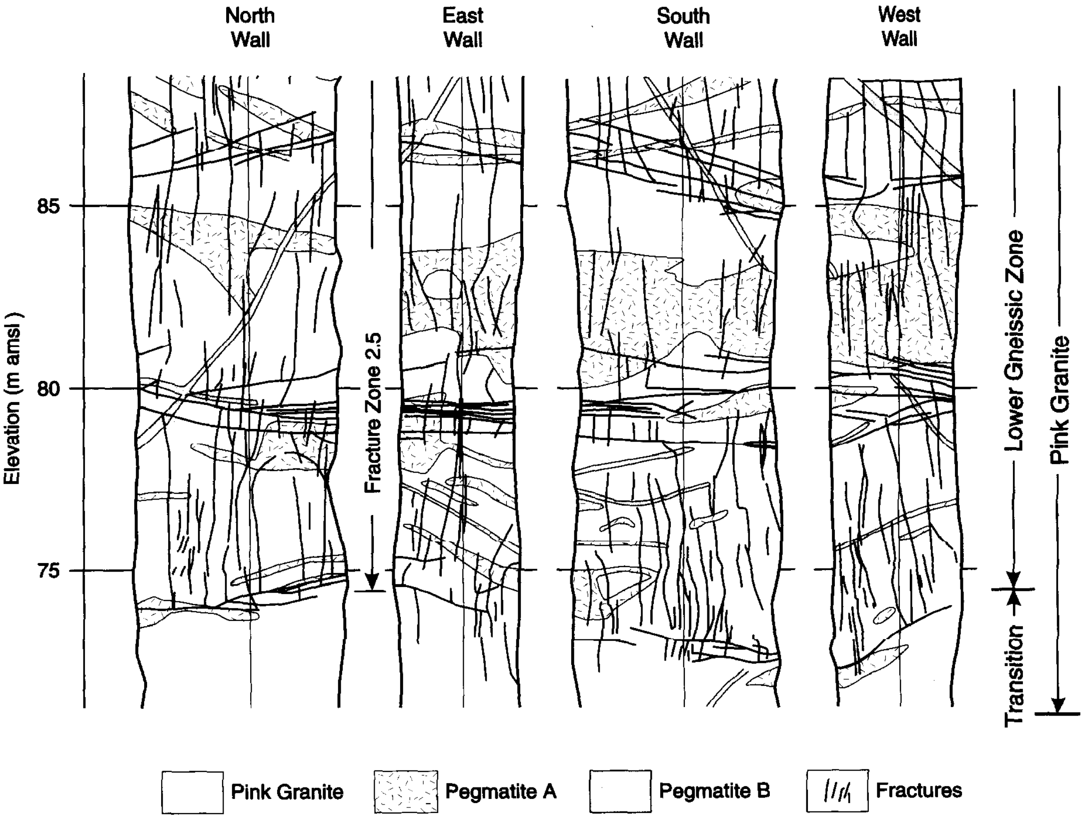
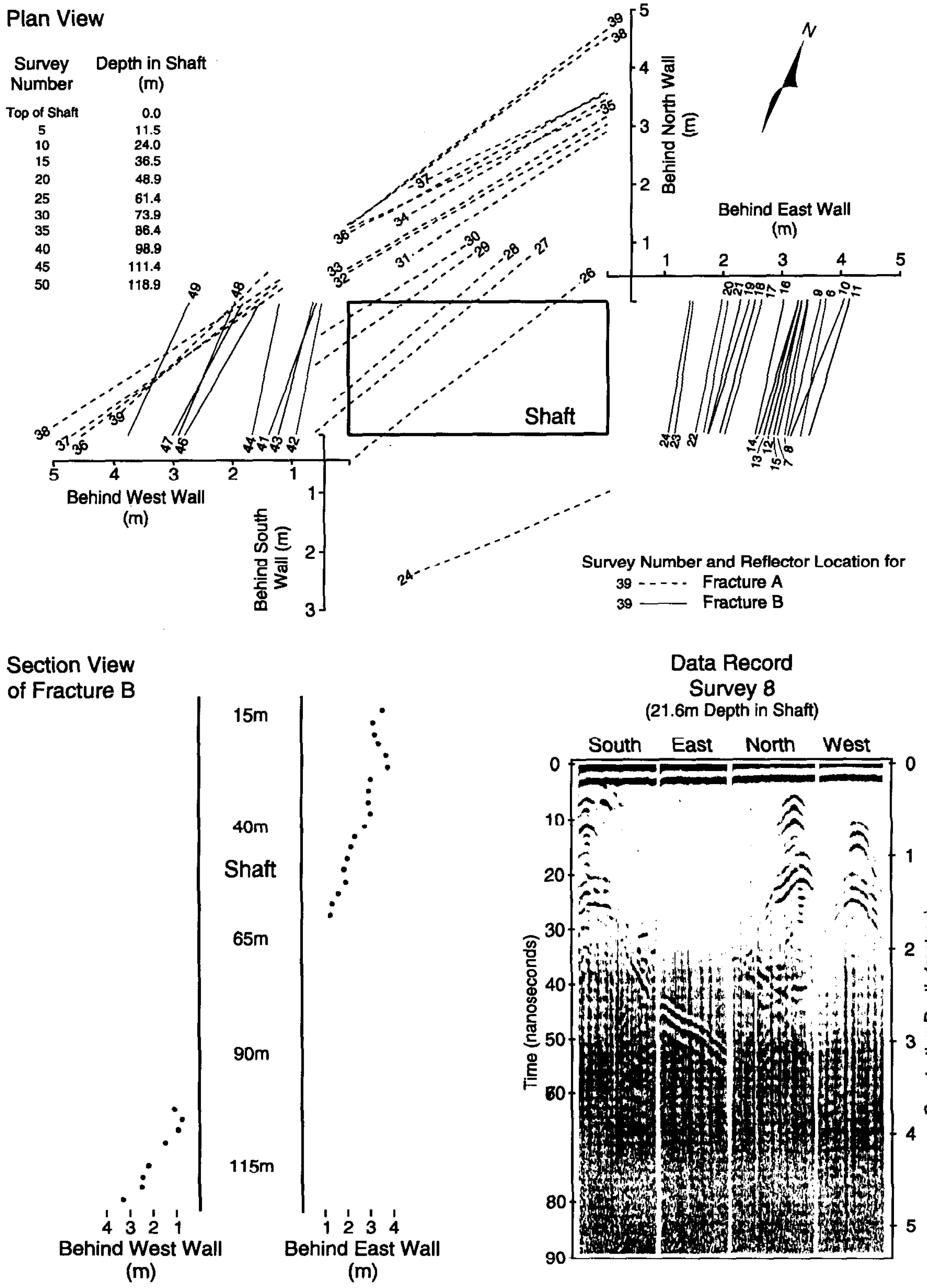


FIGURE 8-1: Example of a Geologic Map of the Underground Research Laboratory Shaft



Plan View

Survey Number	Depth in Shaft (m)
Top of Shaft	0.0
5	11.5
10	24.0
15	36.5
20	48.9
25	61.4
30	73.9
35	86.4
40	98.9
45	111.4
50	118.9

Survey Number and Reflector Location for
39 - - - - - Fracture A
39 ——— Fracture B

Section View of Fracture B

Data Record
Survey 8
(21.6m Depth in Shaft)

FIGURE 8-2: Radar Surveys During the Underground Research Laboratory Shaft Construction using the radar technique. Recent advances in instrumentation and experience in applying the ground penetrating radar method make it possible to detect fractures up to 100 m away from excavation walls in granitic rocks (Holloway et al. 1993).

Convergence pin arrays installed about every 10 m to 15 m down the URL shafts provided valuable information about the in situ stress field, particularly the orientation of the principal horizontal stresses (Lang and Thompson 1986, Lang et al. 1987). In addition, the geological mapping of occurrences of stress-induced notches or breakout zones on the shaft walls can indicate the orientation of the principal horizontal stresses. Stress magnitudes can be inferred from examining these failure zones (Everitt and Gann 1990). Even if localized rock failure is not obvious from the geological mapping, it is possible to map microcrack development during shaft construction using acoustic emission-microseismic monitoring equipment to infer the orientation of the horizontal stress field (Talebi and Young 1989).

The underground characterization methods that would be used during the excavation of the exploratory shafts at a disposal site are listed in Table 8-1. These would involve:

- activities performed continuously as construction proceeds,
- activities performed at special instrument arrays located at different depths in the shafts,
- activities performed in long exploratory boreholes drilled from shaft stations.

8.2.2 Instrument Arrays

During the construction of the exploratory shafts, shaft instrument arrays would be installed at a number of depths. This would require temporary stoppages in shaft construction to allow borehole drilling and the installation of the instruments. During the sinking of the URL shaft construction was halted at ten depth locations to install instrument arrays (Snider et al. 1989a,b). These are shown in Figure 8.3. Figure 8.4 illustrates the layout of a typical instrument, array used in the URL. A typical instrument array at the URL consisted of a radiating pattern of short, horizontal boreholes and short, steeply dipping boreholes extending beyond the bottom of the shaft excavation. Both geomechanical and hydrogeological instruments were installed to measure the near-field conditions in the rockmass and the responses to subsequent excavation of the shaft. Rock displacement instrumentation consisted of multiple-point borehole extensometer systems installed in boreholes collared within 300 mm of the shaft bottom. The borehole fracture monitor-extensometer was used and was able to measure rock displacements of less than 1 μm. Instrumentation, to measure changes in rock stress conditions, was installed in steeply plunging boreholes collared several metres above the shaft bottom and extending to a distance equal to about

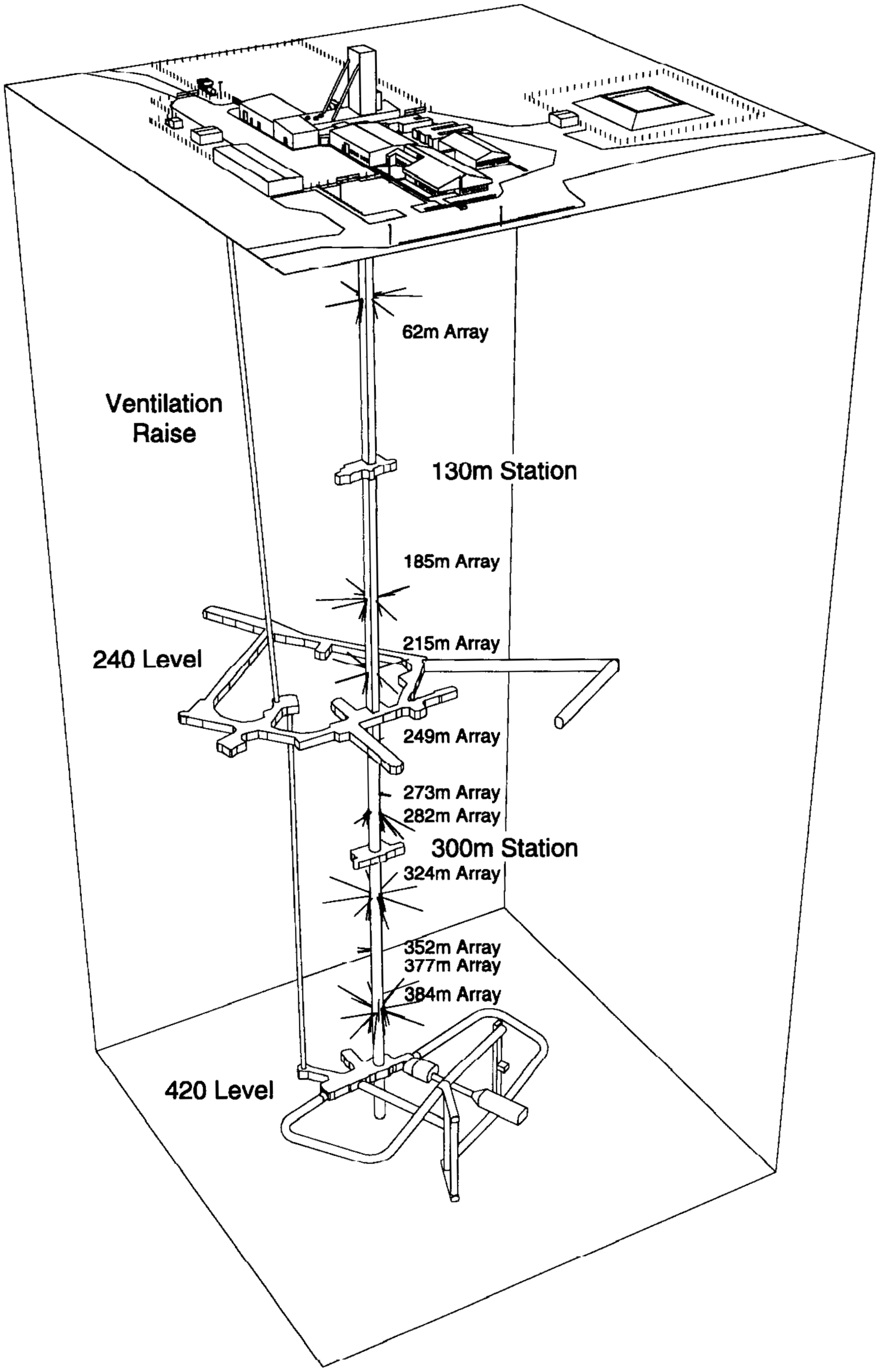


FIGURE 8-3: Instrument Arrays Used During the Underground Research Laboratory Shaft Construction

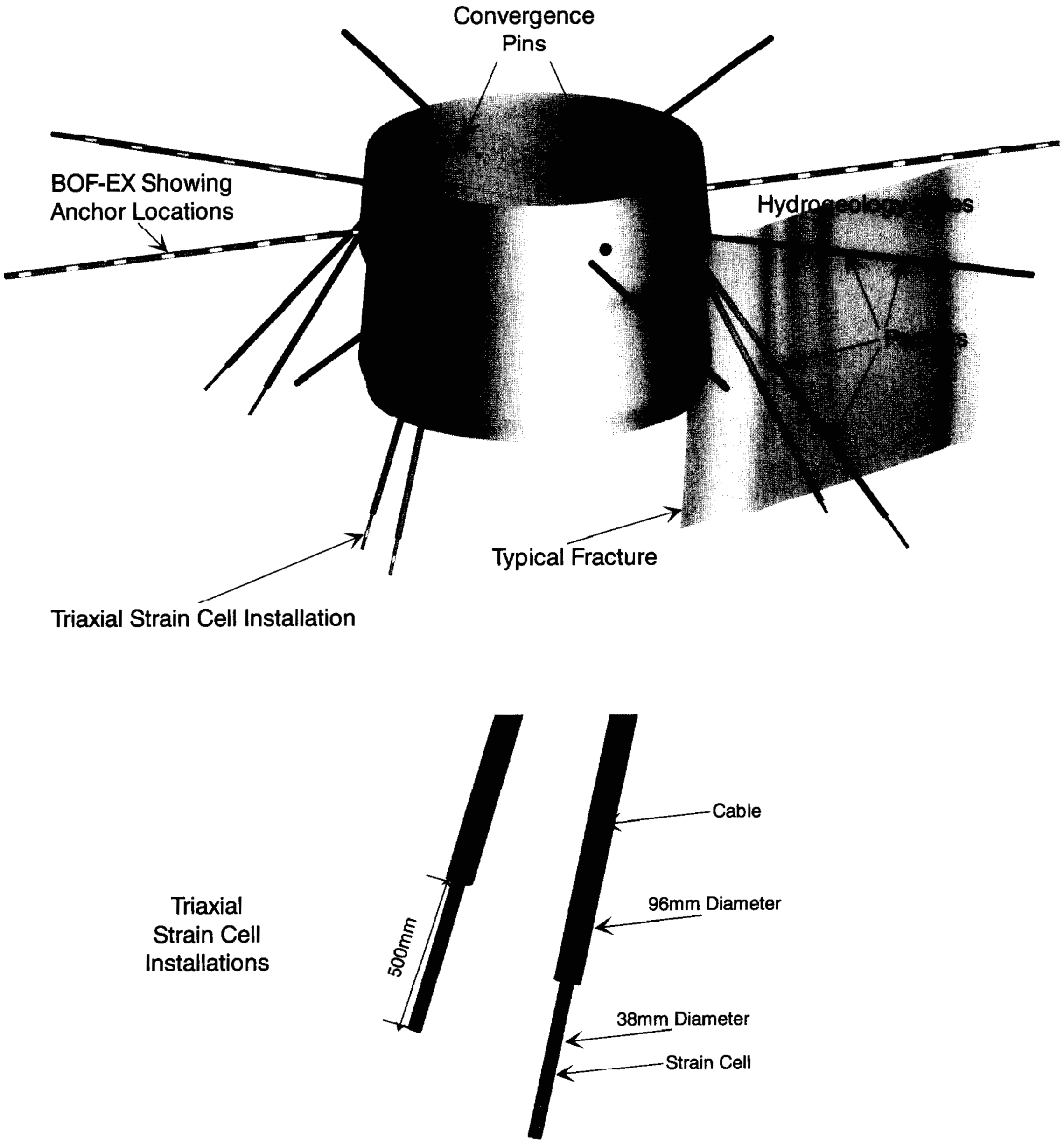


FIGURE 8-4: Typical Instrument Array Layout in the Underground Research Laboratory Shafts

TABLE 8-1

UNDERGROUND CHARACTERIZATION DURING CONSTRUCTION OF EXPLORATORY SHAFTS

Discipline	Activity
1. Continuous Characterization during shaft sinking	
Geology	- Detailed stereophotography and geological mapping of shaft walls and bottom (on a daily basis).
Geomechanics	- Installation and measurement of convergence pin arrays at approximately 10 m intervals.
Geophysics	- Radar and seismic surveys of shaft walls/floor, microseismic monitoring of blast rounds and microcracking.
Hydrogeology	- Continuous recording of piezometric response in far field boreholes surrounding shaft location. - Continuous recording of inflow of groundwater seepage to shaft excavation from both discrete seepage locations and from large segments of the shafts.
Hydrogeochemistry	- Periodic collection of samples of any groundwater seepage locations in the shaft.
2. At instrument arrays in the shaft	
Geology	- Geologic logging of borehole core, examination of core for excavation damage effects.
Geophysics	- Radar and seismic surveys from walls/floor of instrument array, logging boreholes for evidence of excavation damage, seismic tomography surveys between pairs of boreholes.
Geomechanics	- Overcore stress measurements, collection of samples for mechanical rock properties testing, measurements of rock mass convergence.
Hydrogeology	- Permeability determinations in near field boreholes, examination of excavation damage effects on permeability and record changes induced by successive excavation. - Record near field piezometric pressures and observe changes with incremental excavation.

continued . . .

TABLE 8-1 (continued)

	Discipline	Activity
2.	At instrument arrays in the shaft (continued)	
	Hydrogeochemistry	- Obtain groundwater samples from hydrogeological boreholes.
3.	In Exploratory Boreholes Drilled from Shaft Stations	
	Geology	- Core logging.
	Geophysics	- Borehole television and acoustic televiewer logging. - Borehole electrical logging (spontaneous potential, single point resistance, resistivity). - Borehole nuclear logging (natural gamma, gamma-gamma, neutron). - Acoustic velocity logs, full waveform acoustic logs. - Fluid temperature, fluid resistivity, impellar flowmeter. - Single hole radar. - Cross-hole radar and seismic tomography. - Installation of microseismic monitoring devices in some boreholes.
	Geomechanics	- Overcoring for in situ stress determinations. - Hydraulic fracturing for in situ stress determinations.
	Hydrogeology	- Straddle packer hydraulic testing. - Installation of multipacker hydrogeological monitoring systems. - Monitor piezometric pressure variations on a regular basis, combine data with surface-based monitoring.
	Hydrogeochemistry	- Collect groundwater samples from intervals in multipacker hydrogeological monitoring systems on a regular basis.
4.	In Shafts after Excavation is Complete	
	Geology	- Collect additional samples of important rock units and fractures for laboratory examination.

continued . . .

TABLE 8-1 (concluded)

Discipline	Activity
4. In Shafts after Excavation is Complete (continued)	
Geomechanics	- Perform geomechanical tests at instrument array locations. These include: overcore stress measurements, collect core samples for laboratory analysis of mechanical rock properties, collect core samples of undisturbed fractures for laboratory analysis of fracture properties.
Hydrogeology	- Install water rings to collect and monitor groundwater seepage from segments of shaft.
Hydrogeochemistry	- Collect samples of seepage gathered at water rings for chemical analysis.

two shaft diameters below the shaft bottom. Instrumentation developed during the construction of the URL allows both geomechanical and hydrogeological measurements to be made within the same borehole (Thompson and Kozak 1991). This minimizes the number of boreholes required, eliminates the effects that adjacent open boreholes have on the hydrogeological measurements, and allows hydrogeological and geomechanical measurements to be made at the same point within the rockmass (Thompson et al. 1989).

Measurements made at the instrument arrays in an exploratory shaft would include stress, convergence, fracture displacement and permeability. Groundwater seepage rates and hydraulic pressures would also be monitored and groundwater samples would be collected for geochemical analysis. If grouting was required during shaft excavation, the instrument arrays would also provide information on the effectiveness of the grouting operation.

The excavation sequence following the installation of each instrument array would have to be carefully planned and coordinated to minimize blast vibration and concussion effects on the instruments. The sequence would also be designed to provide several small excavation advance steps to maximize the information obtained from the instrumentation. Lang et al. (1987), Martino (1989), Martino et al. (1989) and Martino and Spinney (1990) give examples of results obtained from the instrument arrays used in the URL shaft.

8.2.3 Exploratory Drilling From Shaft Stations

Exploratory boreholes would be drilled laterally out from the shafts at shaft stations. These boreholes would be used to characterize the regions of the rock mass above, below and surrounding the areas initially targeted for the waste emplacement rooms. At the URL exploratory boreholes were drilled downward from shaft stations at 130 m depth and 320 m depth to characterize the rock mass above and surrounding the locations chosen for the 240 m and 420 m experimental levels respectively (Figure 8.5). Additional horizontal exploratory boreholes were drilled outward from a shaft station at 240 m depth to characterize the geologic and hydrogeologic conditions of the volume of rock chosen for the initial experiments at the 240 m level.

Exploratory boreholes drilled from stations in the exploratory shafts would be examined by methods very similar to those used to evaluate boreholes drilled from groundsurface in the surface-based site evaluation phase. Some modifications to equipment and techniques would be required for testing in boreholes with shallow inclinations.

After the completion of borehole surveys, multipacker hydrogeological monitoring systems would be installed in the exploratory boreholes drilled from the shaft stations. These would record groundwater pressures in the rock mass. Special multipacker systems have been developed for this purpose at the URL (Kozak and Davison 1992). The pressure records from these systems would augment the pressure records collected by monitoring the M-P casing systems in the surface-based borehole network. At the URL this approach has provided a comprehensive long-term record of the groundwater pressure conditions in the rock mass surrounding the underground excavations.

In addition, some boreholes would be drilled from the shaft stations to install microseismic acoustic emission monitoring equipment in the rock mass. This equipment would be used to record microseismic signals caused by microcracking in the rock around newly created excavations. At the URL, such measurements were very useful in determining the extent and location of stress-induced cracking in the near field (Talebi and Young 1992, Gibowicz et al. 1991).

8.3 UNDERGROUND CHARACTERIZATION DURING THE CONSTRUCTION OF EXPLORATORY TUNNELS

The primary objective of the excavation and characterization of exploratory tunnels at the candidate site would be to determine the final locations and geometry of the waste emplacement rooms and associated access tunnels. This would involve a thorough evaluation of the rock volumes intended for waste emplacement operations. Particular emphasis would be paid to:

- characterizing the solute transport properties of any nearby fracture zones
- determining the transport properties of the rock volumes between the fracture zones and the locations of proposed waste emplacement rooms.

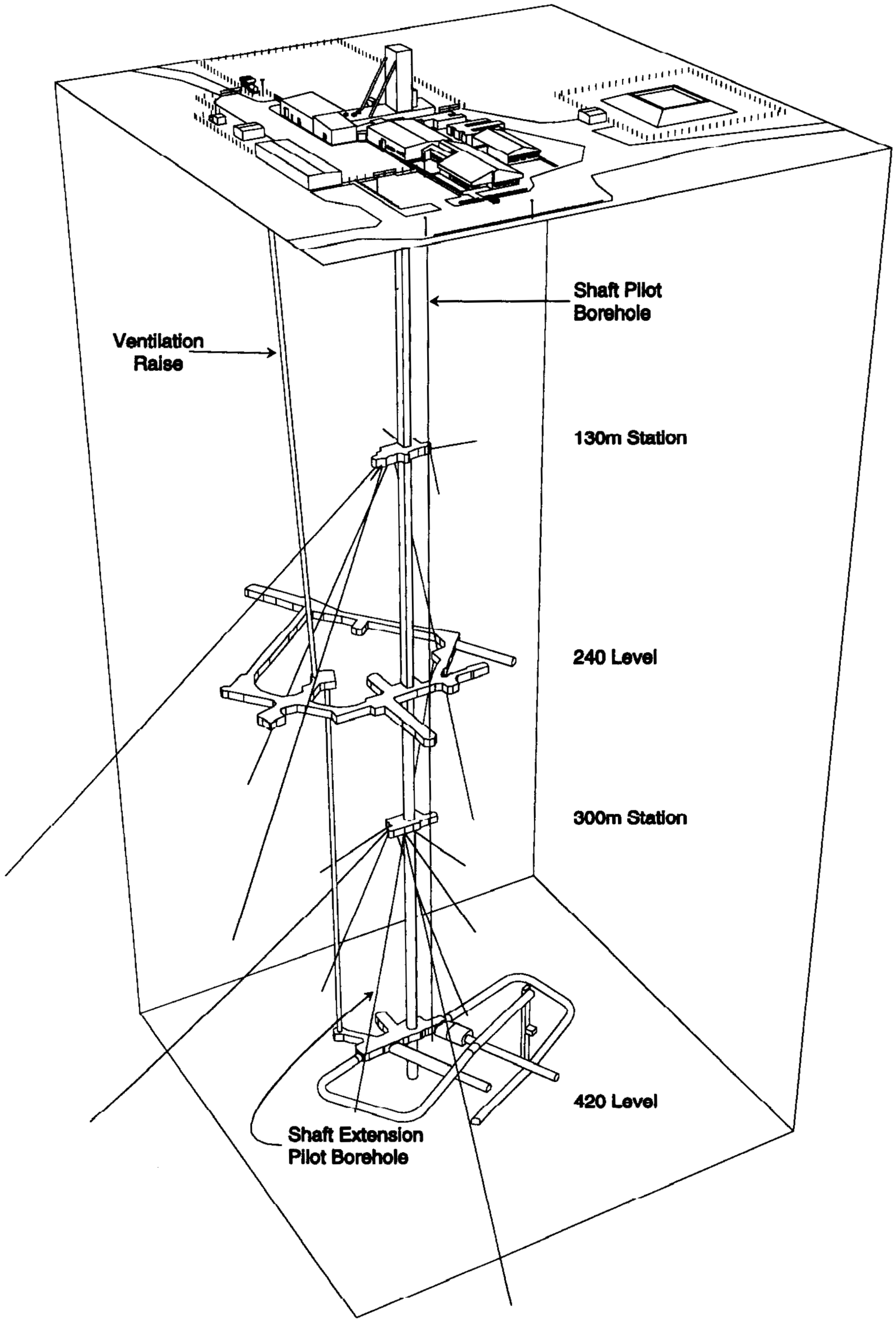


FIGURE 8-5: Layout of Boreholes Drilled From the Underground Research Laboratory Shaft Stations

The resources required to accomplish this would depend on the number and location of the fracture zones, how they connect with the large scale groundwater flow system in the area and the heterogeneity of the rock volumes between the fracture zones and the waste emplacement rooms.

It is expected that exploratory tunnels would be excavated around the entire perimeter of the proposed waste emplacement areas. Both instrument arrays and drill stations would be located along these tunnels to collect the information needed for characterization and design purposes, similar to the arrangements used in the exploratory shafts (Sections 8.2.2, 8.2.3). It would be important to plan the layout of the exploratory tunnels and all boreholes drilled from the exploratory tunnels so that the ability of the rock surrounding the waste emplacement rooms to fulfill its role as a barrier to contaminant movement, would not be jeopardized.

As with previous steps in the site evaluation process, the period involving the excavation and characterization of exploratory tunnels would need to allow for an observational approach to design and construction, to accommodate the site specific conditions that were encountered. The characterization, design and construction activities would need to be carefully integrated during the excavation of the exploratory tunnels.

Figure 8.6 shows the boreholes drilled from the underground tunnels at the 240 m level of the URL to characterize the hydrogeologic conditions of the rock mass at the 240 m level prior to designing and constructing the remainder of the level. Figure 8.7 shows the boreholes drilled from the completed level to characterize potential experimental areas. These boreholes were all equipped with multiple interval monitoring systems to record hydrogeological changes induced by the excavation of the tunnels and by experimental activities (Kozak and Davison 1992). Figure 8.7, also shows the groundwater pressure conditions recorded in these monitoring systems several years after the tunnels had been excavated at 240 m Level.

The characterization activities that would be used in the exploratory tunnels and associated exploratory boreholes would be virtually the same as those used in the characterization of the exploratory shafts. Everitt and Read (1989), Kozak and Davison (1992), Everitt et al. (1992), Martin et al. (1990), Serzu et al. (1994) and Hayles et al. (1992) provide examples from the URL of the application of the methodology for characterizing the exploratory tunnels.

Particular attention would also be paid to determining the extent and effects of the excavation damage zone surrounding the exploratory tunnels. Although this zone is expected to be on the order of a few tens of centimeters thick, it could be very important to controlling groundwater movement and solute transport in the near field of the disposal vault. Depending on its characteristics, the excavation damage zone might require some special seals to control its effects on groundwater movement (Johnson et al. 1994b). Methods have been developed

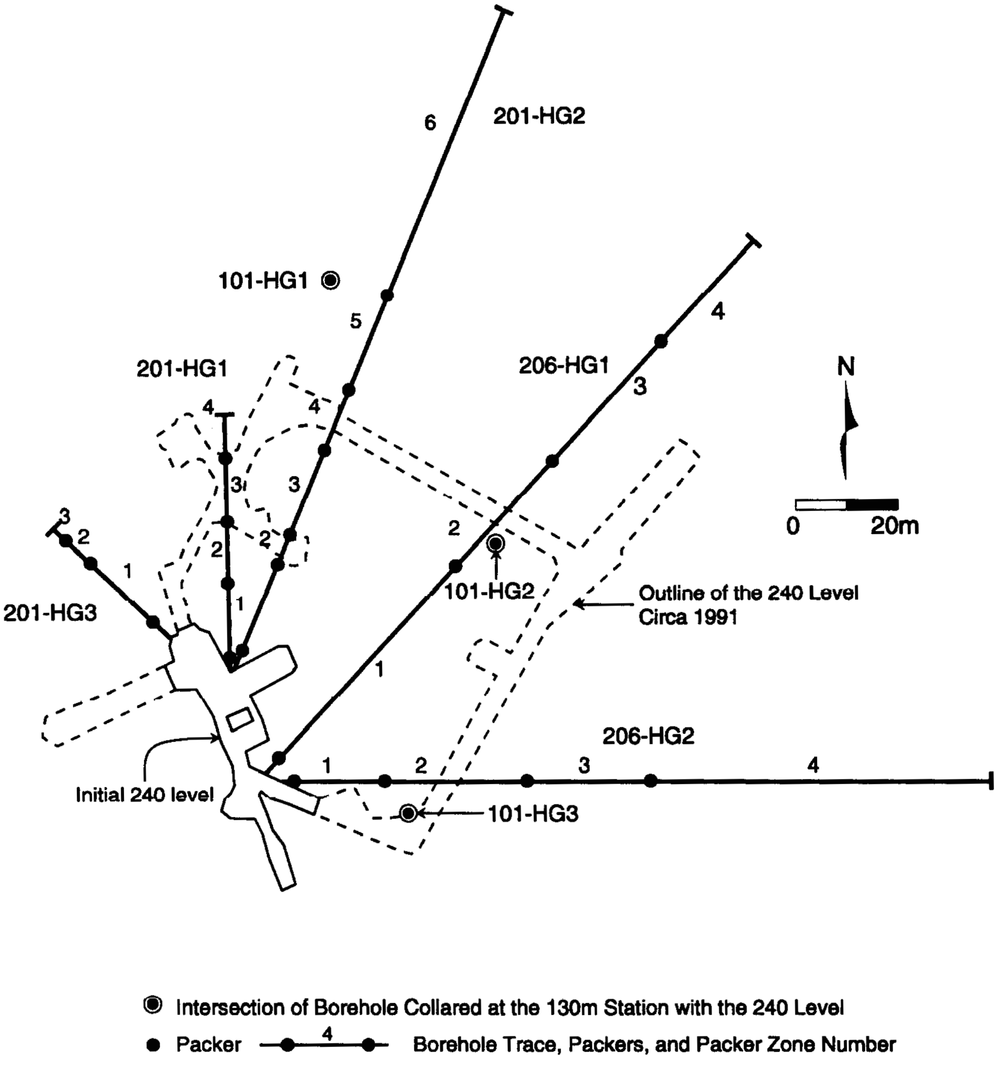


FIGURE 8-6: Borehole Layout in the Initial 240 m Station at the Underground Research Laboratory Relative to Subsequent 240 Level Development

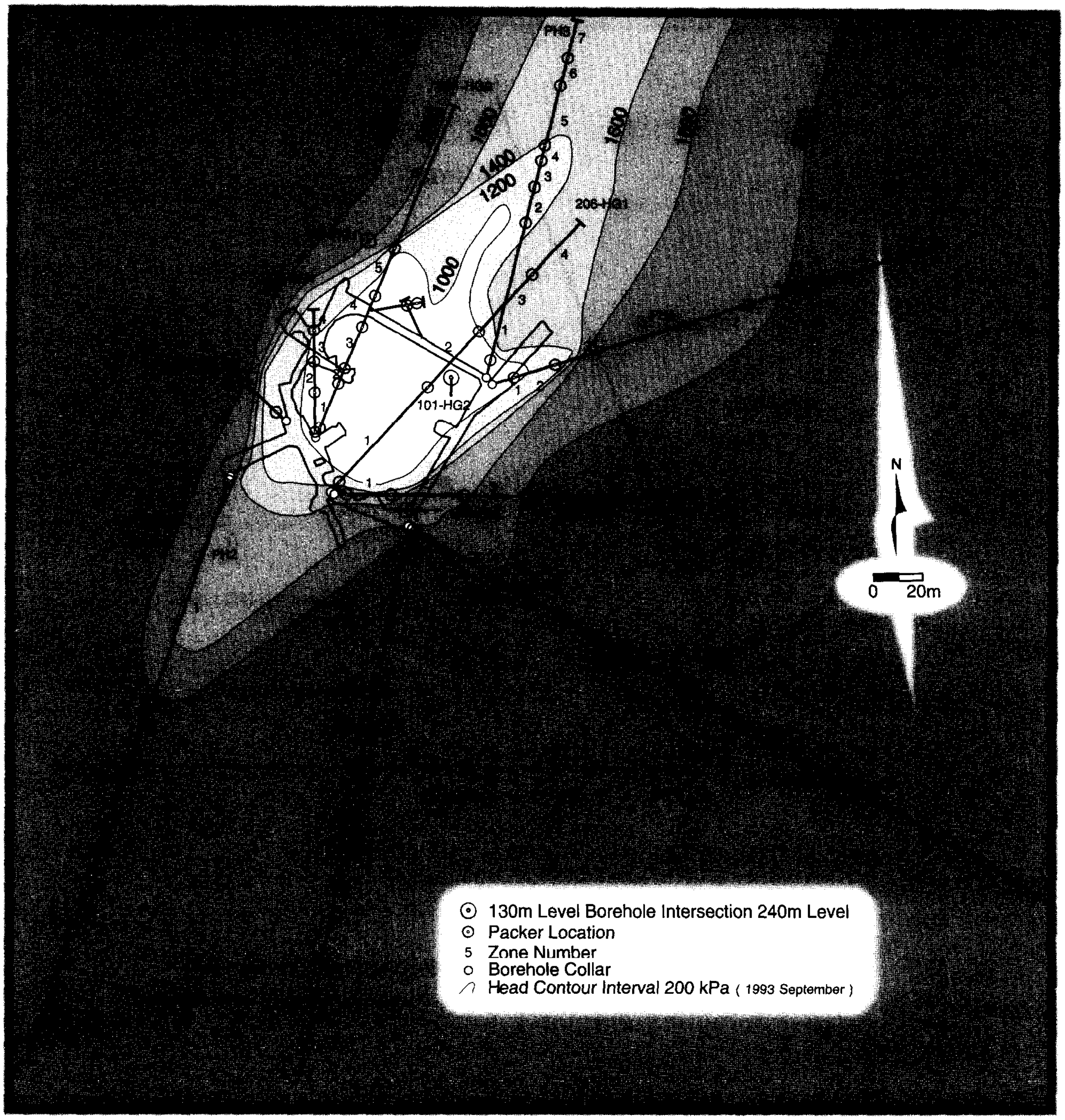


FIGURE 8-7: Borehole Layout at the 240 Level of the Underground Research Laboratory Shown with Piezometric Pressure Distribution

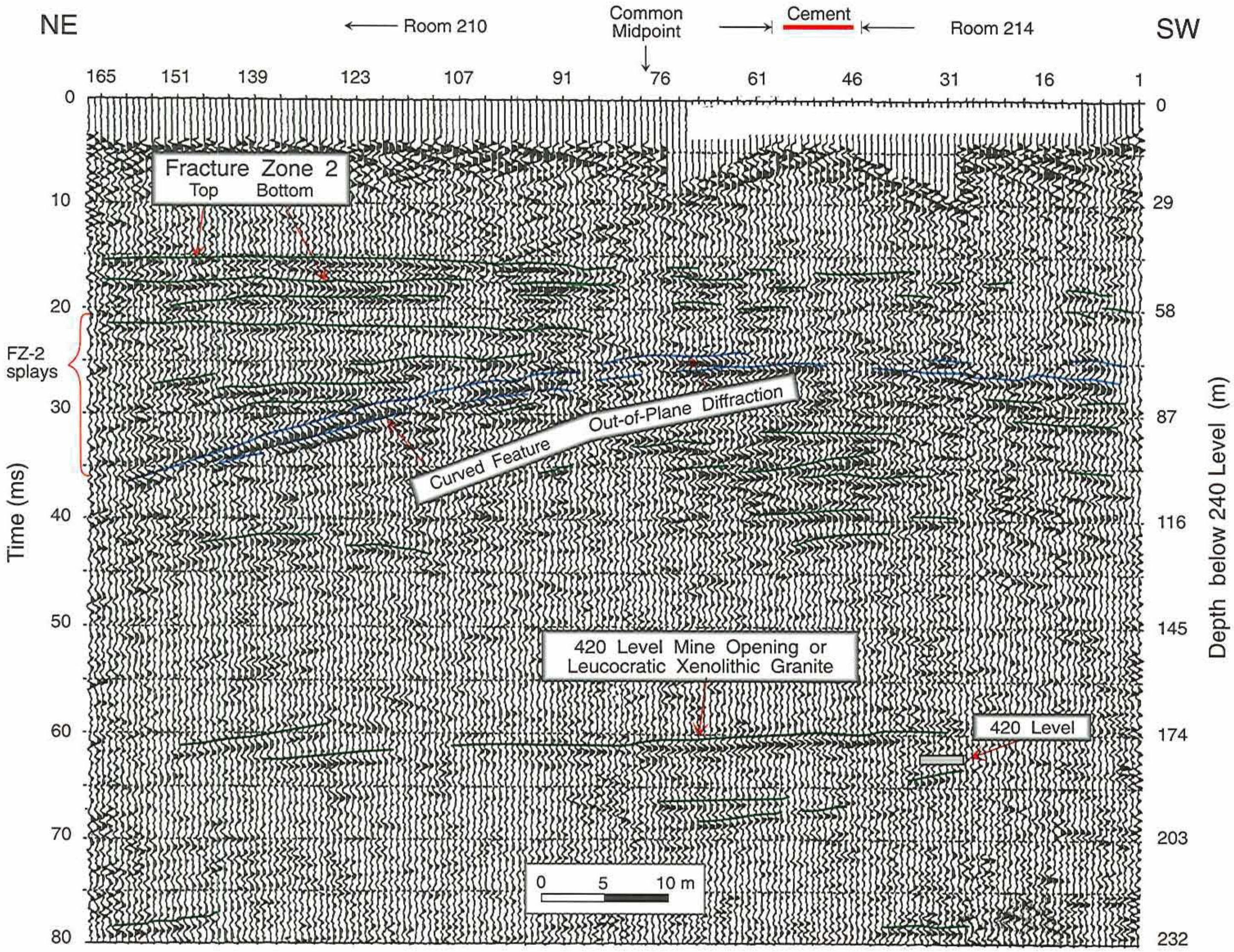


FIGURE 8-8: High Resolution Seismic Reflection Survey from the 240 Level of the Underground Research Laboratory

for characterizing the excavation damage zone surrounding underground tunnels during the excavation of the 240 m and 420 m levels of the URL (Hayles et al. 1992, Martin and Kozak 1992, Martin et al. 1992).

Recent advances have also been made in using high resolution reflection seismic survey techniques from the underground tunnels to detect fracturing and other geologic discontinuities in the surrounding rock. This method was used at the 240 m level of the URL to identify fracture zones in the rock up to 200 m away (Figure 8.8).

It is our judgement that sufficient geotechnical information would exist at a candidate disposal site by the time underground characterization activities were completed from the exploratory tunnels to determine whether or not the site was suitable for constructing and operating a nuclear fuel waste disposal vault. Sufficient information would exist from the surface-based and underground activities to develop a detailed design of the emplacement room configuration, to develop a waste emplacement strategy, and to assess the postclosure safety and environmental impact of disposal at the site.

This assessment could reveal that site-specific design and operating constraints were required at particular underground locations to meet regulatory standards. If such constraints were required, a characterization strategy would likely be needed during facility construction and operations to obtain the information needed for assurance that the constraint was achieved. For example, if there was a constraint on placing waste closer than a certain distance to a major fracture zone and the permeability of the region of rock between the waste and the fracture zone had to be less than a particular value, then characterization would be needed during the construction and operating stages to ensure these specific requirements. On the basis of the work performed at the URL we conclude that the technology currently exists to apply such constraints in practice. A combination of investigations involving surveys and measurements made in exploratory boreholes, from the underground, and geophysical surveys made from the walls of the underground excavations can provide the required information. Examples of these investigations and surveys were described in this chapter.

We believe that the methods for characterizing the rock mass surrounding exploratory excavations have been demonstrated sufficiently at the URL to give us confidence in their feasibility at an actual disposal site. Undoubtedly further advances will be made in methods to characterize the near-field properties of the rock mass from underground excavations before they would need to be applied at an actual candidate disposal site. We are continuing to improve these methods at the URL for future application.

9. SUMMARY OF CHARACTERIZATION METHODS FOR SITE SCREENING AND SITE EVALUATION

The entire period of characterization for siting a disposal vault is expected to span a period of at least about twenty years. It would start with initial site screening activities and proceed through all the subsequent steps of site evaluation. The activities would focus on characterizing geographically smaller areas using surface-based methods and borehole investigations until finally the waste emplacement areas were identified at a candidate site and characterized from exploratory shafts and tunnels. Much site specific information would have been gathered during this time period. This site characterization information would be used to prepare an assessment of the safety and environmental impact of the proposed disposal system at the candidate site as part of the application for approval to construct the nuclear waste disposal vault.

Site characterization activities would continue during the construction and operation stages of the vault as well. These later stages of the project could last twenty-five years or longer, and detailed characterization of the disposal site would continue from the underground excavations to assist in designing the final layout and geometry of the waste disposal rooms and access tunnels. It would also provide data on the mechanical, physical and thermal properties of the rock in each disposal room to design the actual waste emplacement configuration. The design and construction procedures should be sufficiently flexible to allow the detailed site data to be used in developing the optimal underground layout and waste emplacement configurations for the vault.

The information which is obtained during detailed characterization of the underground excavations would be continuously compiled and assessed to determine if it is consistent with what was expected from the analysis of the surface based information. It would also be used to reduce the uncertainty in various parameters and to refine the understanding of the near field rock mass conditions surrounding the disposal vault.

Particular features or areas of the near-field rock mass might be identified which required additional mechanical, hydrogeologic or hydrogeochemical monitoring. The monitoring of the hydrogeological conditions in the farther field rock mass surrounding the vault would also be maintained throughout the project. This would provide data to compare with the predicted hydrogeological behaviour and help to continue improving the understanding of the hydrogeological conditions of the site.

The characterization information which was obtained during the construction and operating stages would also be needed to locate and design the vault seals in the underground excavations. Information about the extent and nature of any excavation-induced damage as well as knowledge of potential natural pathways or zones of weakness in the rock would be needed to develop the appropriate sealing strategy for each situation. The information obtained from the characterization of the exploratory shafts and tunnels would be relied on heavily for this.

Even after waste emplacement operations had ceased in the underground facility and the excavations had been sealed, society might wish to continue monitoring some conditions at the site before making a decision to close the vault. It is conceivable that the period of monitoring for boreholes drilled during the early stages of characterization of a candidate disposal site could exceed 70 years. Although no such length of monitoring experience is yet available, the hydrogeological conditions in the rock mass surrounding the URL facility have been continuously monitored for a period of 10 years so far (beginning in 1983). This monitoring is planned to continue until operations cease at the URL, perhaps until 2010. One of the objectives of this long term monitoring at the URL is to evaluate the longevity and reliability of the hydrogeologic monitoring instruments installed in the boreholes at the URL. Another objective is to develop experience with maintaining and replacing hydrogeologic monitoring instrumentation. This information would be needed when monitoring begins at an actual candidate disposal site. Many improvements in instrumentation would be expected over the several decades spanned by site characterization and monitoring. It would be important to be able to take advantage of these improvements as they occurred.

We expect that existing site characterization methods will be improved and that new methods will be developed during the long time period required to screen, evaluate and select a nuclear fuel waste disposal site and then to construct, operate, decommission and close the disposal vault. However, it is our judgement that existing surface-based, borehole and underground methods are adequate for obtaining the geoscience information needed to commence the siting of a nuclear fuel waste disposal vault in plutonic rock of the Canadian Shield. Davison et al (1994) and Goodwin et al (1994) show how this site specific information is used to assess the safety of the disposal system and its potential environmental impacts, and compare it to current regulatory standards.

In developing site characterization methods for the CNFWMP particular emphasis has been placed on methods to determine the hydrogeological conditions in plutonic rock. This is because the most likely way for contaminants to get from the disposal vault to the surface environment is by movement in groundwater present in the fractures and pores in the rock. Methods have been developed to evaluate the hydrogeologic conditions in plutonic rock at a variety of size scales. These range from the regional scale (required to identify the preferred location for the disposal vault within the context of the hydrogeologic setting of the candidate area) to the very local scale (needed to design the layout of waste emplacement rooms at the candidate vault site and to help select locations for individual containers of waste).

Wherever possible the studies at our field research areas have been integrated to provide case study examples of the way in which the site characterization methods would be used to achieve the objectives of site screening and site evaluation for identifying a suitable location in plutonic rock of the Canadian Shield for a disposal vault. The geoscience work performed at the Whiteshell Research Area comes closest to illustrating the spatial coverage that would be required for siting an actual nuclear fuel waste disposal vault in a candidate area. In particular, the site characterization work at the URL provides a demonstration of how to evaluate the geologic, hydrogeologic, geochemical and geomechanical conditions of a candidate plutonic rock site and how that information would be used to design and construct an actual disposal vault.

The preceding sections of this report have discussed the various surface-based and underground site characterization methods. Examples from studies at the geologic research areas have been used to illustrate their application. These case studies provide evidence that the surface-based, borehole and underground site characterization methods developed by AECL are now sufficiently advanced that they can be used to obtain the geoscience information during site screening and site evaluation for siting a disposal vault in plutonic rock of the Canadian Shield. Tables 9-1 and 9-2 summarize these site screening and evaluation methods. We expect that these methods will continue to be improved and that new methods will likely be developed during the long time period required for implementing the disposal project. Improvements and new developments for site characterization methods are continuing through ongoing research at the URL site and at AECL's other geologic research areas on the Shield. However, the site characterization methods that are currently available are sufficiently well developed to allow siting to commence.

TABLE 9-1

CHARACTERIZATION METHODS USED DURING SITE SCREENING

Method	Type of Information	Use
1. Compilation and analysis of existing data and maps	- Geologic maps and reports	- Determine geologic setting, lithologic distributions and heterogeneity. - Identify large geologic structures such as faults or fracture zones.
	- Airborne geophysical surveys and reports	- Same as above.
	- Soils and surficial geology maps	- Overburden/outcrop distributions, overburden characteristics.
	- Surface water hydrology maps, hydrologic records and topographic maps	- Drainage boundaries, runoff and potential groundwater recharge/ discharge areas, hydro-power potential.
	- Meteorologic data, such as rainfall, precipitation, evaporation	- Combined with above to quantify groundwater recharge/discharge.
	- Forestry, soils and vegetation inventories	- Surface environment assessment.
	- Wildlife surveys	- Surface environment assessmen.
	- Mineral exploration records and reports including borehole records	- Mineral resources, geologic setting, lithology, structural features, subsurface data from borehole records.

continued . . .

TABLE 9-1 (continued)

Method	Type of Information	Use
1. Compilation and analysis of existing data and maps (continued)	- Water resource surveys, including any water supply boreholes	- Generally shallow groundwater conditions including water supply capacity, perhaps groundwater chemistry.
	- Seismic monitoring records	- Historical seismicity of region, combined with regional geological information to determine risk of seismic hazard.
2. Airphoto and topographic map analysis	- Various scales of black and white and colour photographs thermal infra-red photographs, topographic maps	- Lithologic variations, rock outcrop distribution. - Lineament analysis to assess fracturing, faults and fracture zones. - Distribution patterns and habits of wildlife and biota. - Vegetation patterns for identifying lithologic variations, groundwater recharge/discharge conditions. - Local and regional topographic variations. - Surface water drainage patterns and boundaries. - Location of groundwater springs or seepages, or 'deer' or 'moose' licks.
3. Satellite imagery	- Landsat TM (bands 1-7) - SAR images from ERS-1	- Terrain analysis: drainage, vegetation, outcrop distribution.

continued . . .

TABLE 9-1 (continued)

Method	Type of Information	Use
3. Satellite imagery (continued)	- Panchromatic images from SPOT	- Lithologic variations. - Lineament analysis, faults, fracture zones.
4. Reconnaissance geophysical surveys	- Aeromagnetic surveys	- Shape, depth, boundaries of pluton and other lithologies. - linear anomalies caused by lithologic variations, faults or fracture zones.
	- Airborne EM and VLF-EM	- Lithologic variations. - Location of linear features such as faults and fracture zones. - Overburden distribution and thickness.
	- Airborne radiometric	- Boundaries of pluton.
	- Airborne and surface-based gravity	- Shape, depth, boundaries of pluton and surrounding rock units.
	- Reflection seismic profiles	- Large fracture zones and large subsurface variations in lithology.
5. Reconnaissance geological mapping	- Lithologic mapping at outcrops	- Verify and refine existing geologic data base.
	- Fracture mapping at outcrops	- Spatial data on fracture distribution, frequency, orientation and history.

continued . . .

TABLE 9-1 (concluded)

Method	Type of Information	Use
5. Reconnaissance geological mapping (continued)	- Fracture mapping at outcrops adjacent to potential structural features	- Determine location, extent, and orientation of major faults and fracture zones. - Establish any associations with lithologic variations.
	- Petrographic analysis of samples of major lithologic units and fracture infill minerals	- Develop tectonic history of pluton and its geologic structures.
6. Reconnaissance hydrologic/hydrogeologic surveys	- Drainage, runoff patterns, range of water level fluctuations	- Define drainage/watershed boundaries. - Range of volumes of surface water runoff.
	- Examine seepage and spring locations, rock outcrops, exposures of surficial deposits for permeability characteristics	- Initial assessment of groundwater movement, recharge/ discharge relationships.
7. Geochemical surveys	- Surface water chemistry	- Surface water runoff/groundwater discharge relationships.
	- Chemistry of springs and seepages	- Identify groundwater discharge/ flow system relationships.
	- Reconnaissance soil gas surveys	- Identify possible locations of discharge from deep groundwater flow systems.
	- Electrical conductance of lake/river bottom sediments and bottom waters	- Locate discharge of groundwater.

TABLE 9-2

SITE EVALUATION METHODS

TABLE 9-2-1 RECONNAISSANCE SCALE SITE EVALUATION METHODS

Activity	Type of Information	Use
1. Regional Geologic Mapping at a scale of about 1:16000 along traverses .5 km to 2 km apart (more detailed mapping of existing quarried, road cuts or excavations)	Percentage of rock type and spatial distribution of large rock units.	Geometry and size of pluton; folding of pluton; style of pluton contact;degree of granitization.
	Lineament analysis of satellite data, airphotos, topographic maps and, magnetic survey maps.	Fault and fracture zone identification.
	Fracture density.	Relationships to rock type or proximity to faults or fracture zones.
	Fracture orientations, lengths and infilling minerals.	History of fracturing, orientation of stress field in geologic past; locations of faults and fracture zones.
	Collection of rock and fracture infill samples.	Laboratory studies to identify: pressure/temperature (P/T) conditions of pluton emplacement; P/T conditions at episodes of fracturing; absolute dating of pluton deformation history; pluton cooling rates; chemical and mineralogical composition.
2. Airborne Geophysical Surveys	EM and VLF-EMA	Lithologic variations; locate linear features such as faults and fracture zones; map overburden distribution and thickness.

continued . . .

TABLE 9-2-1 (continued)

Activity	Type of Information	Use
2. Airborne Geophysical Surveys (continued)	Magnetic	Depth, shape and boundaries of lithologic units; map linear anomalies caused by lithology, faults or fracture zones.
	Gravity	Shape, depth and boundaries of pluton; distribution of lithologic units.
	Side-scanning radar surveys.	Map linear anomalies that may be caused by lithology, fault zones or fracture zones.
3. Ground-based Geophysical surveys	Gravity transects	Shape, depth and boundaries of pluton and lithologic units.
	Reflection seismic profiles along transects	Subsurface variations in lithology; identify possible location and orientations of major fracture zones or faults in subsurface.
	Ground penetrating radar surveys along transects on rock outcrops	Location and orientation of low-intermediate dipping fracture zones to 100 m depth.
4. Hydrologic/ meteorologic surveys of watersheds	Temperature, windspeed and direction, evaporation rates, precipitation, runoff rates and distributions, levels of surface water bodies; examine springs and seeps	Drainage, runoff conditions; groundwater recharge/discharge characteristics and rates.

continued . . .

TABLE 9-2-1 (concluded)

Activity	Type of Information	Use
5. Water chemistry surveys	Chemistry of surface waters,	Ratios of surface water runoff/groundwater discharge (hydrograph separation).
	Chemistry of water in springs and seepage areas	Chemical character of groundwater discharge areas; locate possible areas where groundwater discharge is from deep flow systems.
6. Soil Gas surveys and surveys of gas buildup beneath ice-covered lakes.	He and Rn concentrations	Identify possible locations of groundwater discharge from deep flow systems.
7. Sonar surveys of lake bottoms	Lake bottom bathymetry, thickness of lake bottom sediments, bedrock surface	Identify linear structures in bedrock beneath lake bottoms that may be faults or fracture zones.
		Identify disruptions in lake sediment that may be related to groundwater discharge, gas release, or to post-glacial dislocations along faults.
8. Mapping spatial distribution of thermal conditions in lakes and electrical conductance of lake bottom sediments	Temperature and chemistry of lake bottom waters	Identify possible locations of groundwater discharge.
9. Mapping patterns of flora and fauna	Species and population distribution	Identify population of endangered or sensitive species; identify sensitive habitats.
	Studies of habits of individuals such as deer or moose	Identify possible locations of deep groundwater discharge.

TABLE 9-2-2 GEOLOGIC DATA COLLECTED AT GRID AREAS AND GEOLOGIC STUDY AREAS

Type of Data	Use
1. Rock types; distributions, interrelationships and relationships to fracturing.	- Determine lithologic structure of pluton. - Determine relationships or controls on development of fracturing or faulting.
2. Large-scale lithologic layering or folding.	- Helps define pluton shape. - Determine any effect on faulting or fracturing such as relationships to location, orientation and density of fracturing. - Helps define deformation and stress history.
3. Xenolith style, orientation and shape.	- Helps define deformation and stress history.
4. Foliations and schlieren.	- Deformation and stress history. - Establish effects on fracture orientation. - Establish relationship to microcrack orientation. - Determination of homogeneity of pluton deformation. - Establish effects on stress measurements.
5. Late magmatic fractures (pegmatites, aplites, quartz veins).	- Establish deformation and stress history. - Determine P/T conditions of formation.
6. Mapping faults, fractures, microcracks dykes and veins - location and geometric characteristics of individual structures. - patterns and geometry of networks of structures.	- Establish history of deformation and stress history. - Determine present day stress orientation. - Establish relationships between style/density and rock types. - Establish geometry of fault zones and related fractures.
7. Rock and fracture specimens for laboratory examination.	- Establish P/T conditions of pluton emplacement. - Establish P/T conditions at episodes of fracturing. - Dating of deformational history and establish pluton cooling rates.

TABLE 9-2-3 CHARACTERIZATION METHODS USED IN DEEP BOREHOLES

Activity/Survey	Information
1. Logging drill core	- Geologic description of lithologic variations. - Location, orientation, geometric characteristics of fractures. - Nature of fracture infillings and alteration.
2. Thermal logging of fluid in borehole	- Geothermal gradient, locations of inflows and outflows of groundwater in borehole.
3. Flow logging of fluid in borehole	- Locations of more permeable intervals of borehole.
4. Acoustic televiewer survey	- Location, orientation of fractures and other irregularities in the borehole wall such as due to lithologic variations or stress-induced breakouts.
5. Borehole television camera survey	- Location, orientation of fractures. - Character of fracture infillings. - Lithologic variations.
6. Standard geophysical logs	- Fracture locations. - Salinity of borehole fluid. - Lithology variations.
7. Single hole radar survey	- Location, orientation and extent of large fractures away from the borehole (up to 70 m).
8. Hydraulic fracturing	- Magnitude (and in some cases orientation) of state of stress in rock.
9. Groundwater sampling using straddle packer equipment	- Groundwater chemistry variations.
10. Hydrogeological testing using straddle packer equipment	- Permeability and storage conditions of near field surrounding borehole.
11. Installation of multiple-packer (M-P) casing system	- Provides long term access to hydraulically isolated intervals for hydrogeological testing and monitoring and groundwater sampling.

continued . . .

TABLE 9-2-3 (concluded)

Activity/Survey	Information
12. Hydraulic tests and geochemical sampling through M-P casing system	- Permeability/storage conditions of near field surrounding boreholes. - Groundwater chemistry variations. (provides data for use in developing an understanding of the large scale groundwater flow conditions).
13. Long-term piezometric pressure monitoring using M-P casing system	- Hydraulic head distribution. (data for use in developing large scale groundwater flow system understanding).

TABLE 9-2-4 UNDERGROUND CHARACTERIZATION DURING CONSTRUCTION OF EXPLORATORY SHAFTS

Discipline	Activity
1. Continuous Characterization during shaft sinking	
Geology	- Detailed stereophotography and geological mapping of shaft walls and bottom (on a daily basis).
Geomechanics	- Installation and measurement of convergence pin arrays at approximately 10 m intervals.
Geophysics	- Radar and seismic surveys of shaft walls/floor, microseismic monitoring of blast rounds and microcracking.
Hydrogeology	- Continuous recording of piezometric response in far field boreholes surrounding shaft location. - Continuous recording of inflow of groundwater seepage to shaft excavation from both discrete seepage locations and from large segments of the shafts.
Hydrogeochemistry	- Periodic collection of samples of any groundwater seepage locations in the shaft.
2. At instrument arrays in the shaft	
Geology	- Geologic logging of borehole core, examination of core for excavation damage effects.
Geophysics	- Radar and seismic surveys from walls/floor of instrument array, logging boreholes for evidence of excavation damage, seismic tomography surveys between pairs of boreholes.
Geomechanics	- Overcore stress measurements, collection of samples for mechanical rock properties testing, measurements of rock mass convergence.
Hydrogeology	- Permeability determinations in near field boreholes, examination of excavation damage effects on permeability and record changes induced by successive excavation. - Record near field piezometric pressures and observe changes with incremental excavation.

continued . . .

TABLE 9-2-4 (continued)

Discipline	Activity
2. At instrument arrays in the shaft (continued)	
Hydrogeochemistry	- Obtain groundwater samples from hydrogeological boreholes.
3. In Exploratory Boreholes Drilled from Shaft Stations	
Geology	- Core logging.
Geophysics	- Borehole television and acoustic televiewer logging. - Borehole electrical logging (spontaneous potential, single point resistance, resistivity). - Borehole nuclear logging (natural gamma, gamma-gamma, neutron). - Acoustic velocity logs, full waveform acoustic logs. - Fluid temperature, fluid resistivity, impeller flowmeter. - Single hole radar. - Cross-hole radar and seismic tomography. - Installation of microseismic monitoring devices in some boreholes.
Geomechanics	- Overcoring for in situ stress determinations. - Hydraulic fracturing for in situ stress determinations.
Hydrogeology	- Straddle packer hydraulic testing. - Installation of multipacker hydrogeological monitoring systems. - Monitor piezometric pressure variations on a regular basis, combine data with surface-based monitoring.
Hydrogeochemistry	- Collect groundwater samples from intervals in multipacker hydrogeological monitoring systems on a regular basis.
4. In Shafts after Excavation is Complete	
Geology	- Collect additional samples of important rock units and fractures for laboratory examination.

continued . . .

TABLE 9-2-4 (concluded)

Discipline	Activity
4. In Shafts after Excavation is Complete (continued)	
Geomechanics	- Perform geomechanical tests at instrument array locations. These include: overcore stress measurements, collect core samples for laboratory analysis of mechanical rock properties, collect core samples of undisturbed fractures for laboratory analysis of fracture properties.
Hydrogeology	- Install water rings to collect and monitor groundwater seepage from segments of shaft.
Hydrogeochemistry	- Collect samples of seepage gathered at water rings for chemical analysis.

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