NUCLEAR WASTE
MANAGEMENT
ORGANIZATION

SOCIÉTÉ DE GESTION
DES DÉCHETS
NUCLÉAIRES

August 2003

NWMO BACKGROUND PAPERS
4. SCIENCE AND ENVIRONMENT

4-2 CHARACTERIZING THE GEOSPHERE IN HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT

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NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts –** describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.
2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.
3. **Health and Safety –** provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.
4. **Science and Environment –** provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.
5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.
6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.
7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

EXECUTIVE SUMMARY

The Nuclear Waste Management Act, Bill C-27, specifies that three approaches must be considered for the management of high-level radioactive wastes. The three approaches are: deep geological disposal in the Canadian Shield, storage at reactor sites and centralized storage either above or below ground. The rock surrounding a disposal vault, any sediments overlying the rock and the groundwater in the rock and sediments is defined as the “Geosphere”. For subsurface disposal or storage systems for high-level radioactive waste, the geosphere can provide a buffer between the spent fuel and the biosphere. The importance of the geosphere and geospheric research is dependent on the approach, being least important for above ground storage, and most important for a below ground management system. The degree to which the geosphere will be relied upon to minimize the impact on the biosphere of potential releases of radionuclides from a waste repository or vault determines the relative importance of the geosphere within the overall waste management system. For above ground short-term storage approaches, the waste repository or vault is in close proximity to the biosphere; the geosphere does not contribute to the isolation of the accessible repository from the human environment. Long-term disposal systems, located deep within the geosphere, are designed to be passive. The geosphere is an integral and important part of the high-level radioactive waste management system. It acts to isolate the repository from the human environment. Even if the waste canisters in the repository are breached, the slow rate of the groundwater flow and the range of geochemical immobilization and retardation processes help to ensure that radionuclides continue to be confined within the engineered barrier system and the immediately surrounding rock, so that further radioactive decay takes place. Therefore, a required attribute of the geosphere for a deep disposal system is that groundwater flow at repository depths be either stagnant or sluggish. The plutonic rock of the Canadian Shield has this attribute. Other geosphere formations that also have this property are bedded salts and shales. Within Ontario, there are significantly more potential disposal sites in plutonic rock than either salt or shale.

Plutonic rock is widespread throughout the Canadian Shield. The characteristics of plutonic rock have been studied at the Whiteshell Research Area (WRA) near Lac du Bonnet Manitoba. The fracture, hydraulic, thermal, mechanical and hydrogeochemical properties of the crystalline rock have been extensively studied at the Underground Research Laboratory at the WRA. The hydrogeochemical data indicate that below 500 m at the URL, groundwaters are very saline, reducing, and old. The groundwater can be considered as essentially stagnant over the period of concern for a waste facility (1,000,000 years). The very low permeability of the rock supports this conclusion.

The characteristics of the URL were used as the basis of a 1994 Environmental Impact Statement on the concept for disposal of Canada’s nuclear fuel waste. The EIS was extensively reviewed. The concerns of the Scientific Review Group (SRG) and Seaborn Environmental Assessment Panel have been addressed by a Second Case Study and more recently by the ongoing Third Case Study (TCS). Research on site characterization and safety assessment methods for the deep disposal concept in plutonic rock are an important part of the TCS. Contributions to geospheric research relative to a deep disposal system include: improved methods for data management and visualization, the development of a new generation of site characterization and safety assessment models that resolve the concerns of the SRG, new methods for assessing the complex network of

discrete fracture zones that are found in the Canadian Shield, the study of the temperature regime and deep permafrost that occurs in northern sections of the crystalline rock of the Canadian Shield, the determination of the hydraulic and transport properties of moderately fractured rock and discrete fractures, the continued study of the hydrogeochemistry of crystalline rock, and the study of the impact of glaciation-deglaciation cycles on a deep repository.

From our understanding of the glaciation-deglaciation cycles that have occurred for the last 900,000 years, it is virtually certain that the geosphere above a deep repository will be covered by ice for a significant interval in the next 100,000 years. The impact of the thickness of the ice and remoteness of the biosphere are important factors that must be considered in safety assessment. The presence of the ice cover should significantly reduce the possible impact of a repository on the biosphere.

Current engineering, construction and hazardous waste handling practices are at a standard that ensures safe short-term surface and near surface high-level radioactive waste management; however, the waste remains accessible and is not isolated from the human environment. Geosphere research and knowledge is well developed and there is a broad and diverse base of expertise for such systems. In comparison, research for deep geologic storage or disposal is highly specialized and has been undertaken by a relatively small group of scientists and engineers. The EIS and SCS were largely the work product of AECL. An important outcome of the SRG and Seaborn Environmental Assessment Panel reviews of the EIS is that a wider base of expertise is now being developed to undertake research on the deep geologic disposal of high-level radioactive waste. This research base includes scientists and engineers in numerous consulting firms and universities as well as those at AECL, OPG and other power authorities.

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1. INTRODUCTION

This report, written for the Nuclear Waste Management Organization, presents an overview of geospheric research for a high-level radioactive waste management (HLRWM) system. The "Geosphere" is defined in this report as the rock underlying a surface storage site or surrounding a subsurface disposal or storage vault, any sediments overlying the rock, and the groundwater in the rock and sediments (Davison el al., 1994). The current management practice in Canada is the storage of HLRW at reactor sites. The concept for the deep geologic disposal of HLRW in crystalline rock of the Canadian Shield was put forth in an Environmental Impact Statement (EIS) by AECL (1994). Data for the EIS were based largely on experience at the Underground Research Laboratory (URL) in the Whiteshell Research Area (WRA) near Lac du Bonnet, Manitoba. The EIS and supporting documents was the subject of numerous reviews. The Scientific Review Group (SRG, 1995) presents a review of the data, site characterization and assessment of the geosphere documented in the EIS. The Seaborn Environment Assessment Panel (1998) also presents a review of the geosphere as a subsystem for the deep geologic disposal of HLRW. The role of the geosphere in an update of the concept for deep disposal, known as the Second Case Study (SCS), is documented in Stanchell et al. (1996). Currently, Ontario Power Generation through its Deep Geologic Repository Technology Program, is sponsoring research that will develop methods and data to evaluate and demonstrate the long-term safety of a deep geologic repository for high-level radioactive waste.

1.1 BACKGROUND

1.1.1 ALTERNATIVES FOR HLRWM

The *Nuclear Fuel Waste Act*, Bill C-27, defines the approaches that must be considered for high-level radioactive waste management. The Bill specifies that a mandate of the *Nuclear Waste Management Organization* (NWMO) is that

1) Within three years after the coming into force of Bill C-27, the waste management organization shall submit to the Minister of Natural Resources, or such member of the Queen's Privy Council for Canada as the Governor in Council may designate as the Minister for the purposes of Bill C-27, a study setting out
    - *(a)* its proposed approaches for the management of nuclear fuel waste, along with the comments of the Advisory Council on those approaches; and
    - *(b)* its recommendation as to which of its proposed approaches should be adopted.
2) Each of the following methods must be the sole basis of at least one approach:
    - *(a)* deep geological disposal in the Canadian Shield, based on the concept described by Atomic Energy of Canada Limited in the *Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste* and taking into account the views of the environmental assessment panel set out in the *Report of the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel* dated February 1998;
    - *(b)* storage at nuclear reactor sites; and

(c) centralized storage, either above or below ground.
As defined in Bill C-27, ``nuclear fuel waste" means irradiated fuel bundles removed from a commercial or research nuclear fission reactor.

The geosphere is an important component or subsystem of each of the management approaches but its importance does vary with approach. For storage of HLRW at either reactor sites or a centralized facility that is above ground, the repository or vault provides the buffer between the waste and the biosphere; because of the proximity of the repository to the biosphere, the geosphere provides little protection. The importance of the geosphere as a barrier increases for below ground centralized storage and is most important for deep geologic disposal. For these situations, the geosphere can act to either minimize or completely alleviate any impact on the biosphere of potential releases from a repository.

In general, the requirement for monitoring of the geosphere at a repository or vault to detect failure of the waste containment system is inversely proportional to the effectiveness of the geosphere as a buffer between the repository and the biosphere and proportional to the accessibility of the repository. Monitoring of highly accessible surface storage systems throughout their design life is essential. Monitoring of a closed deep geologic repository that is not accessible is difficult if not impossible; the system is designed to be passive. The feasibility of invoking remedial action to rectify contamination of the geosphere caused by repository failure is also inversely proportional to the importance of the geosphere as a buffer. When the geosphere provides either short-term or no protection of the biosphere, as can be the case for a surface storage system, a remedial action contingency plan is part of the system design. This plan specifies the actions that will be taken to remediate or control the releases of radionuclides from a failed system.

1.1.2 THE HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT SYSTEM

The components or subsystems of a high-level radioactive waste management system are illustrated in the flow diagram of Figure 1. The flow diagram is applicable to the three management approaches being considered by the NWMO. The elements of the system include the waste package or containers, the vault or repository environment into which the waste package is placed, the geosphere that surrounds the vault and the biosphere. The biosphere includes the human environment. The waste package and vault are part of the near field where the influence of the high-level radioactive waste may have an impact on the properties of the surrounding materials. The geosphere and biosphere are part of the far field; properties of these systems can be considered to be independent of the waste. The geosphere and the biosphere can evolve or change; present day conditions may not be applicable in the future. Climate change and anthropogenic activities are examples of influences that can change the state of the geosphere and biosphere. Therefore, the state of the far field systems must be considered in the long-term disposal or storage of HLRW. Paleo-climate and the cycles of glaciation-deglaciation that have occurred in Canada over the last 900,000 years is one of the most important changes in the state that must be considered in the design and assessment of a HLRW repository.

Within the integrated system, the geosphere subsystem and its evolving state, determines the setting for the repository or vault. The geosphere also receives radionuclides that may migrate from the repository or vault. The potential for these radionuclides to move or migrate through the geosphere to the biosphere is an issue in the assessment of the safety of a repository. The communication between the geosphere subsystem and the repository subsystem includes groundwater potentials at the repository geosphere boundary, repository parameters used in the geosphere analysis, fluid flux and updates in time (e.g., permeability, porosity). The parameters that link the repository or vault subsystem to the geosphere are the nuclide flux and temperature.

A critical aspect of the assessment of a waste management system is the mathematical description or modeling of the behaviour of the system through time. Predictions of performance are best accomplished using mathematical models that represent the system. When the synergy between subsystems (for example, geosphere and repository) or processes is described in a fully coupled manner, the result is a fully integrated performance assessment model. In comparison, a partially integrated performance assessment model defines the links between the subsystems in an uncoupled manner with the models of the various subsystems being solved sequentially. The repository and waste package subsystems, as illustrated in Figure 1, can be integrated to represent the vault system as defined in Goodwin et al. (1994).

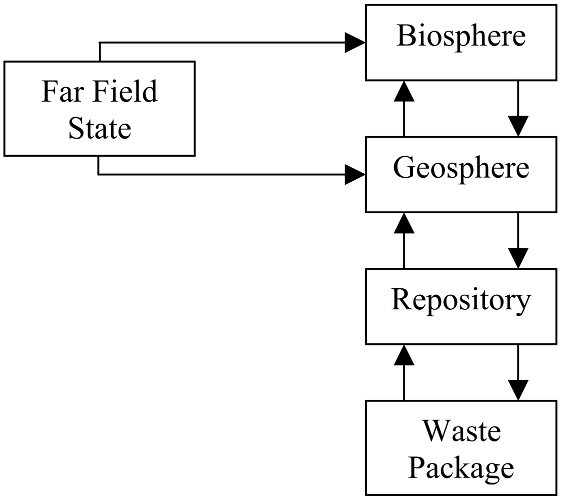

Figure 1: System Model Configuration Flow Diagram

The system components must be reviewed within the framework of the goals and purpose of a performance assessment. Performance assessment is the quantitative prediction of the long-term performance of either a subsystem or the entire system, often relative to a performance standard. For example, does the temperature of the rock within the immediate vicinity of the repository or disposal vault stay within the technical specifications at all times, or what is the maximum release rate of a specific radionuclide from the waste package? Integrated performance assessment, or safety assessment, is the evaluation of the entire system with respect to safety-related standards such as radiological risk to humans and other biota.

1.1.3 DEEP GEOLOGICAL DISPOSAL CONCEPT

The concept for the deep geological disposal of Canada's used nuclear fuel involves isolating the waste in corrosion-resistant containers emplaced and sealed within a vault at a depth of 500 m to

1000 m below the ground surface. Possible host materials for the vault include plutonic rock of the Canadian Shield, clay, salt and shale formations. Two configurations of the concept are presented in Figure 2; the upper figure illustrates in-floor placement of the used fuel in titanium containers while the lower figure depicts in-room placement of the waste in copper containers. A cross-sectional view of a vault with in-room placement is shown in Figure 3. As part of the normal evolution for the used fuel repository, container failure and subsequent release of radionuclides to the environment is expected to occur through groundwater pathways. As a consequence, an understanding of groundwater flow patterns and rates within a fractured crystalline terrain setting is germane to developing strategies for repository siting, site characterization work programs, and putting forth a safety case for long-term repository performance. Within such fractured flow domain settings groundwater flow will be governed, among other factors, by temporal and spatial hydraulic boundary conditions, host rock permeability distributions, groundwater compositions and the prevalence of transmissive structural discontinuities.

The technical feasibility of the used nuclear fuel disposal concept, and its impact on the environment and human health, were first presented in comprehensive detail in an Environmental Impact Statement (EIS) (Davison et al., 1994). The Second Case Study (SCS) evaluated the long-term effects of a hypothetical repository in a geological setting with a permeable host-rock condition (Stanchell et al., 1996). In an actual repository implementation, it would be advantageous to locate the disposal vault in a hydraulically favourable setting within the large-scale groundwater flow system of a candidate site. In such a setting, the engineering of the repository would be adapted to the lithological, hydrogeological, geochemical, geothermal, geomechanical, and geomicrobiological conditions of the host rock formation (Stanchell et al., 1996). For example, radioactive waste generates heat that can have an impact on the surrounding geosphere. The lithology or rock type, strength or geomechanical properties and the temperature or geothermal properties of the rock must be considered in determining the amount of used fuel that can be placed in a given volume of the rock.

1.1.4 THE SAFETY CASE

NAGRA, the National Cooperative for the Disposal of Radioactive Waste in Switzerland, states that the safety case is the set of arguments and analyses used to justify the conclusion that a specific repository system will be safe. It includes in particular, a presentation of evidence that all relevant regulatory safety criteria can be met. It includes a series of documents that describe the system design and safety functions, illustrate the performance, present the evidence that supports the arguments and analyses, and that discuss the significance of any uncertainties or open questions in the context of decision making for further repository development (NAGRA, 2002).

The strength of geological disposal as a waste management option was defined by NAGRA (2002). They state that radioactive waste needs to be managed in a way that ensures the safety of humans and the protection of the environment, as well as providing security from malicious intervention, now and in the future. According to current understanding, geological disposal is the only waste management option that offers long-term passive safety. Placing the waste in a deep rock formation favours security in that it reduces the possibility of irresponsible interference. The NAGRA conclusion echoes that of Canadians who have studied or reviewed HLRWM including Aiken et al. (1977) and the Seaborn Environmental Assessment Panel (1998).

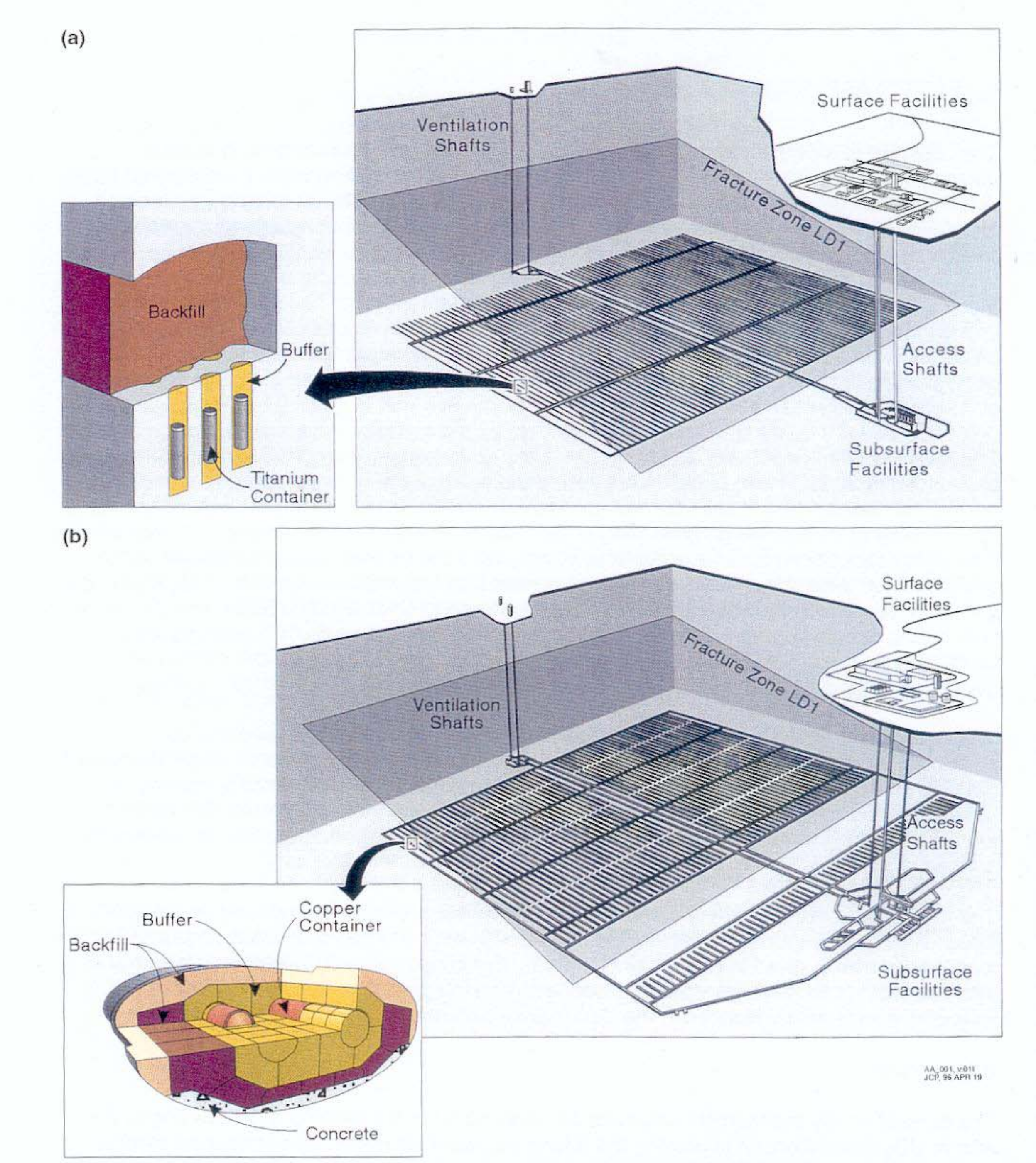

Figure 2: Illustration of Two Hypothetical Used Fuel Repositories; (a) depicts the repository that was evaluated in the EIS case study (borehole emplacement of titanium containers, (b) shows the repository that was evaluated in the Second Case Study (in-room emplacement of copper containers) (from OPG annual report 2001, figure 9, page 24)

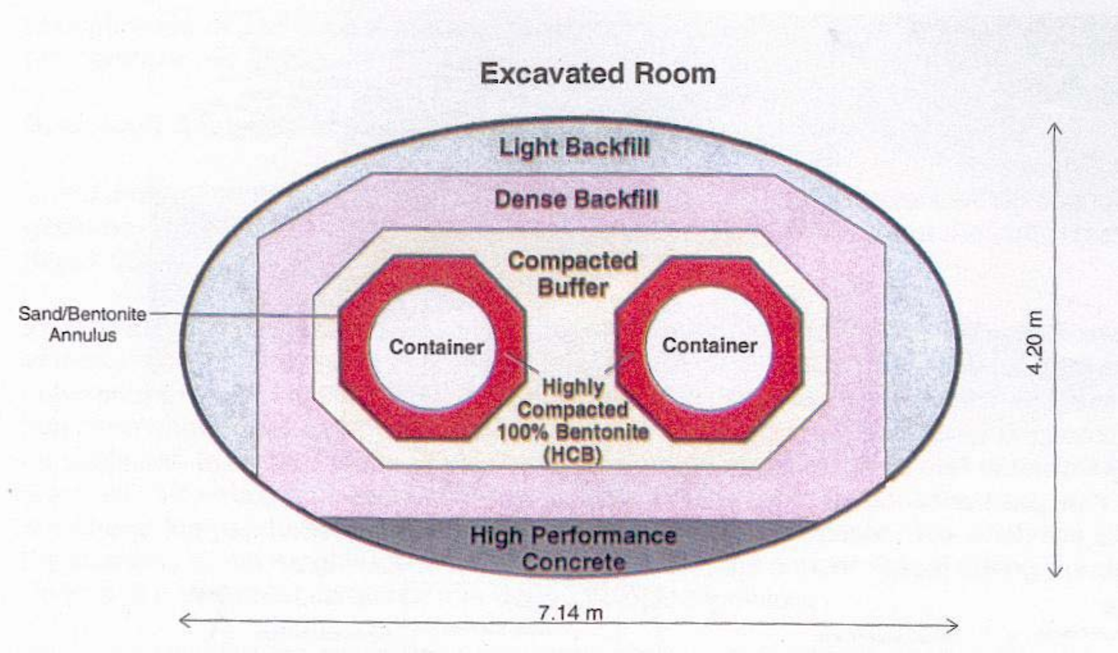

Figure 3: Cross-sectional view of an emplacement room sealing system arrangement for an in-room emplacement alternative. (OPG annual report 2003, figure 2, page 10)

1.2 SCOPE AND OBJECTIVES

This report presents a discussion of the research being conducted in Canada on the role of the geosphere in determining the performance of a HLRWM facility. The importance of the geosphere is a function of the management approach. For surface and near surface HLRWM systems, the geosphere is not expected to provide a significant buffer between the repository or vault and the biosphere. The operating life of these facilities is short relative to that of a deep geologic repository. For such near surface or surface systems, considerable experience can be derived from the design, construction, operation and remediation (where necessary) of hazardous waste facilities; a significant body of geosphere literature and practice exists for such systems. The review of this literature and experience as it applies to either surface or near surface management approaches for HLRW is beyond the scope of this report.

In Canada, substantial research has been undertaken on the characterization of crystalline rock as a potential geosphere setting for a deep repository or vault for waste disposal. In comparison, there is relatively little if any information available on the suitability of the clay, salt and shale formations in Canada as potential settings for a HLRWM facility. Ontario Power Generation's research initiatives on the Deep Geologic Repository Technology Program are summarized in their 2003 annual report (OPG, 2003). All geoscience research projects that are reviewed in the annual report deal with crystalline rock. There was no indication that geoscience research is being undertaken in Canada on alternative settings for a HLRWM facility. As a consequence, the descriptions in this report of alternative formations such as shale, salt or clay are brief.

The geosphere is an important component of a deep geologic HLRWM facility. This report emphasizes the role of the geosphere for such a facility. The characterization of the geosphere is presented in Chapter 2. The section includes a discussion of the geosphere setting for a deep geologic repository from both a Canadian and an Ontario perspective. Hydrogeology and the movement of water in the geosphere is an important consideration in the selection and assessment of a candidate site; Chapter 2 therefore comments on the recharge area concept that has been put forth by some experts as a tool to guide site selection. In Canada, the current regulatory policy for the disposal of radioactive waste requires that quantitative estimates of the health effects to an individual and effects on natural populations of other biota be made for a period of 10,000 years following closure, with reasoned arguments regarding potential effects for periods beyond 10,000 years (Davison et al., 1994). Assessments to 100,000 years or more have been made in recent studies. Therefore, the Chapter also includes an introduction to the evolution of climate and its profound impact on a deep geologic repository in a Canadian setting. It is highly probable that for some period during which there is a potential for a repository to release radionuclides to the geosphere, that a glacial layer of significant thickness will cover the geosphere at the site and during such a period, the state of the biosphere will be radically different from that of today.

The deep geologic HLRWM program in Canada has focused on the study of the geosphere at the Whiteshell Research Area (WRA) near Lac du Bonnet Manitoba; Chapter 3 reviews aspects of the literature from this program. There is considerable experience in HLRWM in other countries. The concepts in Finland, Sweden and Switzerland are briefly presented in Chapter 4 of this report. Finally, numerical simulation models are an important part of the characterization and assessment of a candidate HLRWM facility. The models continue to evolve; the dramatic increase in computer power in recent years coupled with our improved ability to manipulate and visualize data has made some of the simplifying assumptions of earlier models unnecessary. Chapter 5 discusses some of the geosphere simulation models that are used in the Canadian program.

2. CHARACTERIZATION OF THE GEOSPHERE

2.1 GEOSPHERE SETTING

The function of the geosphere in the disposal system is to protect the high-level radioactive waste, container, and vault seals from natural disruptions and human intrusion; to maintain conditions in the vault favourable for the long term waste isolation; and to limit the rate at which contaminants from the waste could move from the vault to the biosphere (Davison et al., 1994, pg 95).

The alternative geosphere settings for a deep disposal vault include (AECL, 1994):

- plutonic rock of the Canadian Shield,
- bedded salt deposits of the interior sedimentary basins
- shales of the interior sedimentary basins

The distribution of these formations in Canada is shown in Figure 4. Aiken et al. (1977) recommended that since Ontario is the main producer of high-level radioactive waste, the first disposal facility should be a national facility located in Ontario. This constraint, if imposed, is a limiting factor in the consideration of other geosphere alternatives such as salt domes and unmetamorphosed tuff and basalt; while these formations can be found in Canada, they do not occur in Ontario (AECL, 1994, page 328). Other acceptable geosphere media for a HLRWM facility include metamorphosed tuff and basalt; however, these formations occur on the Canadian Shield in areas of significant economic activity such as mining or other resource development. Clay may also be an acceptable host media for a HLRWM facility.

As defined in the AECL (1994) and by NAGRA (2002), a deep geologic disposal system performs a number of functions relevant to long-term security and safety. These safety functions are as follows (from NAGRA, 2002, page IV):

- *Isolation from the Human Environment*: The safety and security of the waste, including fissile material, is ensured by placing it in a repository located deep underground, with all access routes backfilled and sealed, thus isolating it from the human environment and reducing the likelihood of any undesirable intrusion and misapplication of the materials. Furthermore, the absence of any currently recognizable and economically viable natural resources and the lack of conflict with future infrastructure projects that can be conceived at present reduces the likelihood of inadvertent human intrusion. Finally, appropriate siting ensures that the site is not prone to disruptive events and processes detrimental to its long- term stability.
- *Long-term confinement and radioactive decay within the disposal system:* Much of the activity initially present decays while the wastes are totally contained within the primary waste containers, particularly in the case of the spent fuel (SF) and high-level waste (HLW), for which the high integrity steel canisters are expected to remain unbreached for at least 10,000 years. Even after the canisters are breached, the stability of the SF and HLW waste forms in the expected environment, the slowness of the groundwater flow and the range of geochemical immobilization and retardation processes ensure that radionuclides continue to be largely confined within the engineered barrier system and the immediately surrounding rock, so that further radioactive decay takes place.
- *Attenuation of releases to the environment:* Although complete confinement cannot be provided over all relevant times for all radionuclides, release rates of radionuclides from the waste forms are low, particularly from the stable SF and HLW waste forms. Furthermore, a number of processes attenuate releases during transport toward the surface environment and limit the concentrations of radionuclides in that environment. These include radioactive decay during slow transport through the barrier provided by the host rock and the spreading of released radionuclides in time and space by, for example, diffusion, hydrodynamic dispersion and dilution.

The key features and phenomenon contributing to the safety functions for a deep geologic disposal system are defined by NAGRA (2002) as the Pillars of Safety. These are (from NAGRA, 2002, page VII):

- *The deep underground location of the repository* in a setting that is unlikely to attract human intrusion and is not prone to disruptive geological events and to processes unfavourable to long-term stability

- *The host rock* which has a low hydraulic conductivity, a fine, homogeneous pore structure thus providing a strong barrier to radionuclide transport and a suitable environment for the engineered barrier system
- *A chemical environment* that provides a range of geochemical immobilization and retardation processes, favours the long-term stability of the engineered barriers and is itself stable due to a range of chemical buffering reactions
- *The bentonite buffer* as a well-defined interface between the canisters and the host rock that ensures that the effects of the emplacement of tunnels and the heat-producing waste on the host rock are minimal, and that provides a strong barrier to radionuclide transport and a suitable environment for the canisters and the waste forms.
- *SF and HLW canisters* that are mechanically strong and corrosion resistant in the expected environment and provide absolute containment for a considerable period of time
- *SF and HLW waste forms* that are stable in the expected environment

These attributes are the same as those stated in the EIS for Canadian HLRWM facilities.

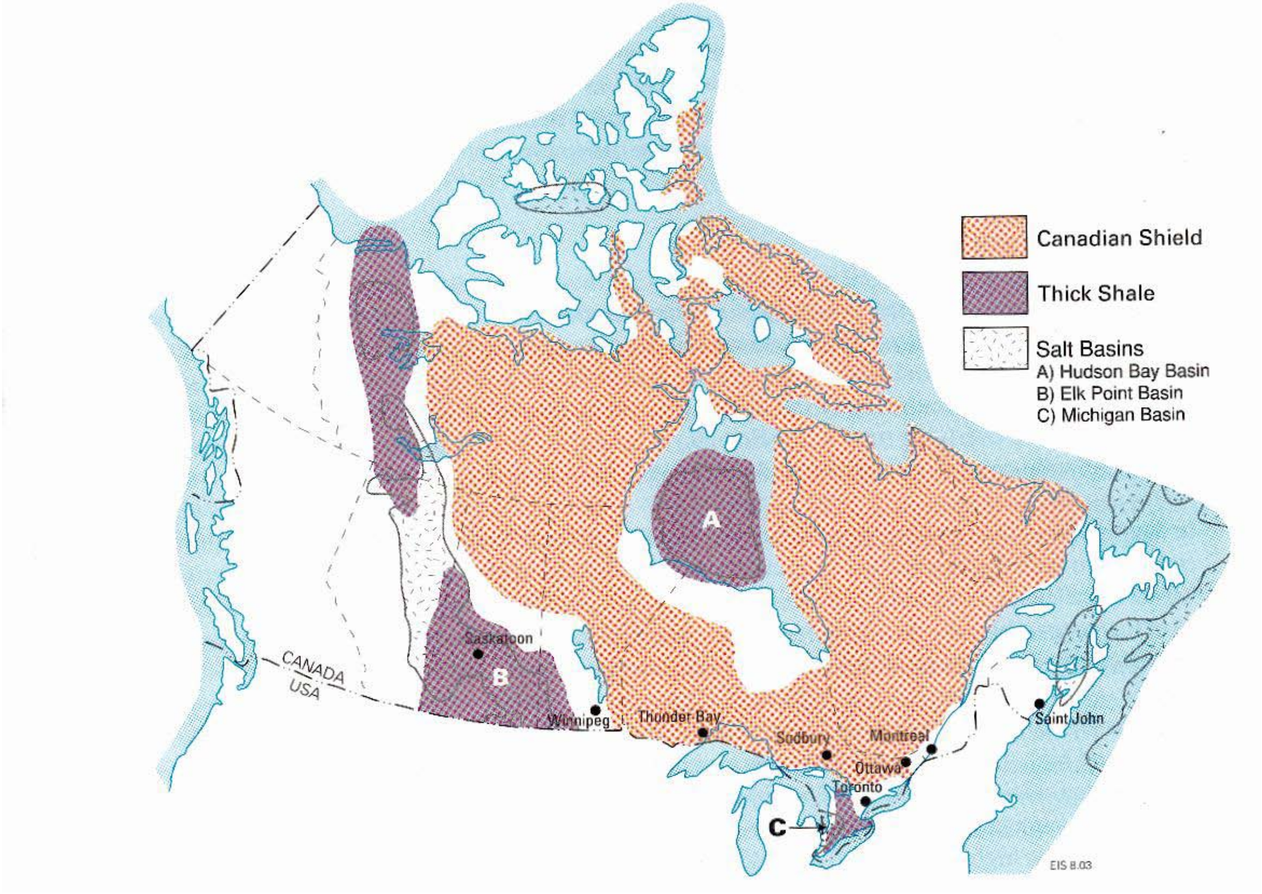

Figure 4: Some geologic formations in Canada (AECL, 1994, Figure 8-3, page 329)

2.2 THE CANADIAN SHIELD

The Canadian Shield is subdivided into major units called provinces or orogens on the basis of the structure, history of deformation, and the estimated age of formation of the rock (refer to

Figure 5). The Superior Province of the Canadian Shield is the largest exposure of Aerchaen Rock (> 2.5 billion years old) on earth. The Superior Province consists of east-west trending belts of metavolcanic, metasedimentary, and plutonic rock. It comprises most of the Shield of Ontario and was formed between 3.1 and 2.7 billion years ago. The last major deformation occurred around 2.5 billion years ago. However, the rock was repeatedly faulted and locally intruded during the Proterozoic period (2.5 billion to 570 million years ago) (Davison et al., 1994, pg 96).

The plutonic rock of the Canadian Shield (Figure 6) would provide a stable environment for a deep geologic repository. The rock is widely distributed and occurs in regions of low topographic relief where the driving force for groundwater movement is likely to be low (AECL, 1994). As stated in the AECL (1994, page 98), “The wide distribution of plutonic rock in Ontario (refer to Figure 6) was an important consideration in the initial decision to concentrate nuclear waste management research on plutonic rock of the Shield as the preferred disposal medium for Canada”.

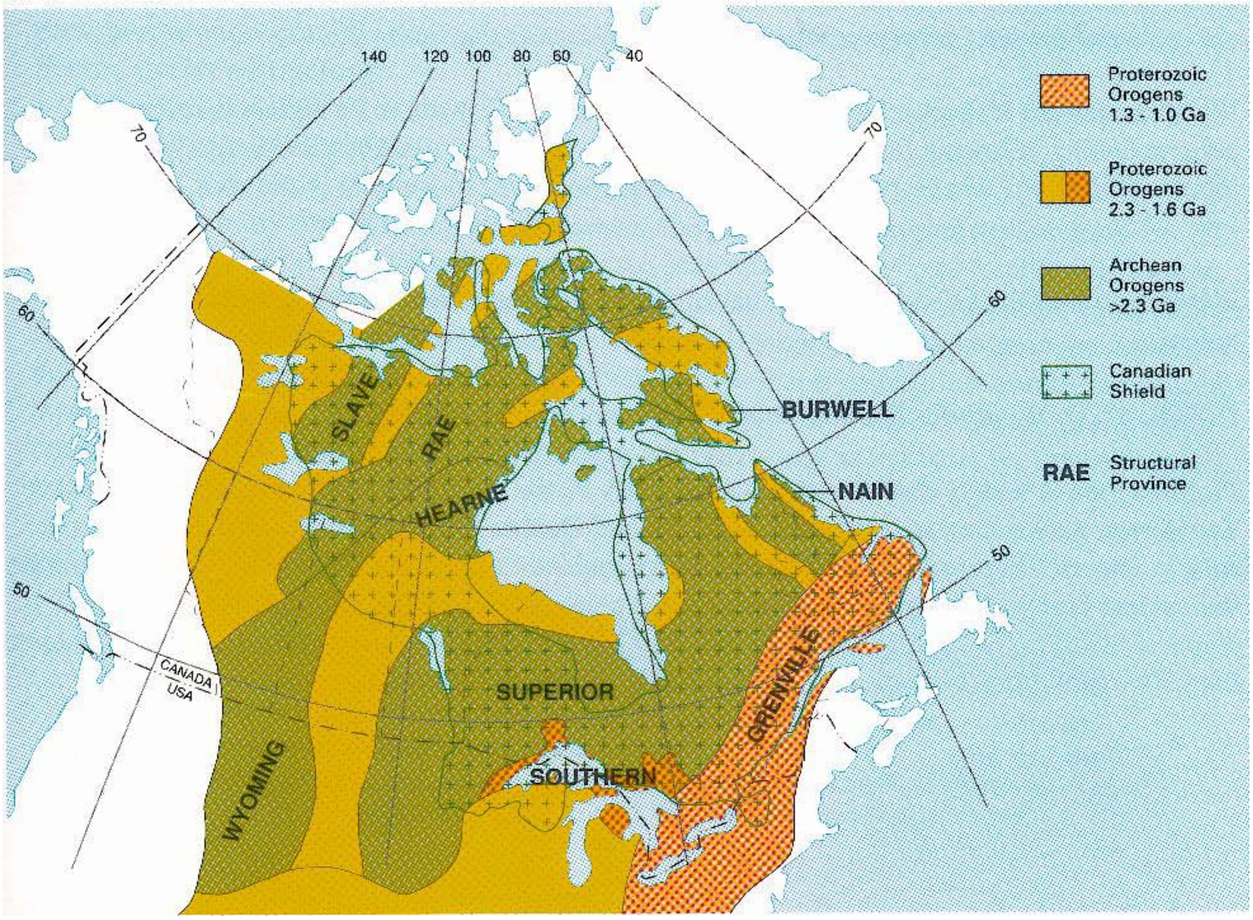

Figure 5: Major subdivisions of the Canadian Shield (AECL, 1994, Figure 4-2, page 97)

A deep geological nuclear waste disposal facility should be located in a region that is geologically stable and likely to remain stable (AECB, 1987; NAGRA, 2002). Geological stability is a characteristic that would clearly enhance the protective function of the geosphere. It would also enhance the long-term predictability of conditions in the vault. Earth movements or seismicity is one of the natural processes that has the potential to disrupt a disposal vault or the surrounding geosphere. The Canadian Shield is the least seismically active portion of the Noth American continent and one of the least seismically active regions in the world; however, earthquakes do occur periodically (AECL, 1994). Figure 7 shows the location of earthquakes for the period 1978 to 1992. The seismic activity is clustered near three geologic structural features: the Kapuskasing structural zone, the Timiskasing rift and the Ottawa/St. Lawrence rift. However, large areas of the Shield and plutonic rock had only minimal or no seismic activity. In summary, large areas of stable plutonic rock occur within the Ontario section of the Canadian Shield.

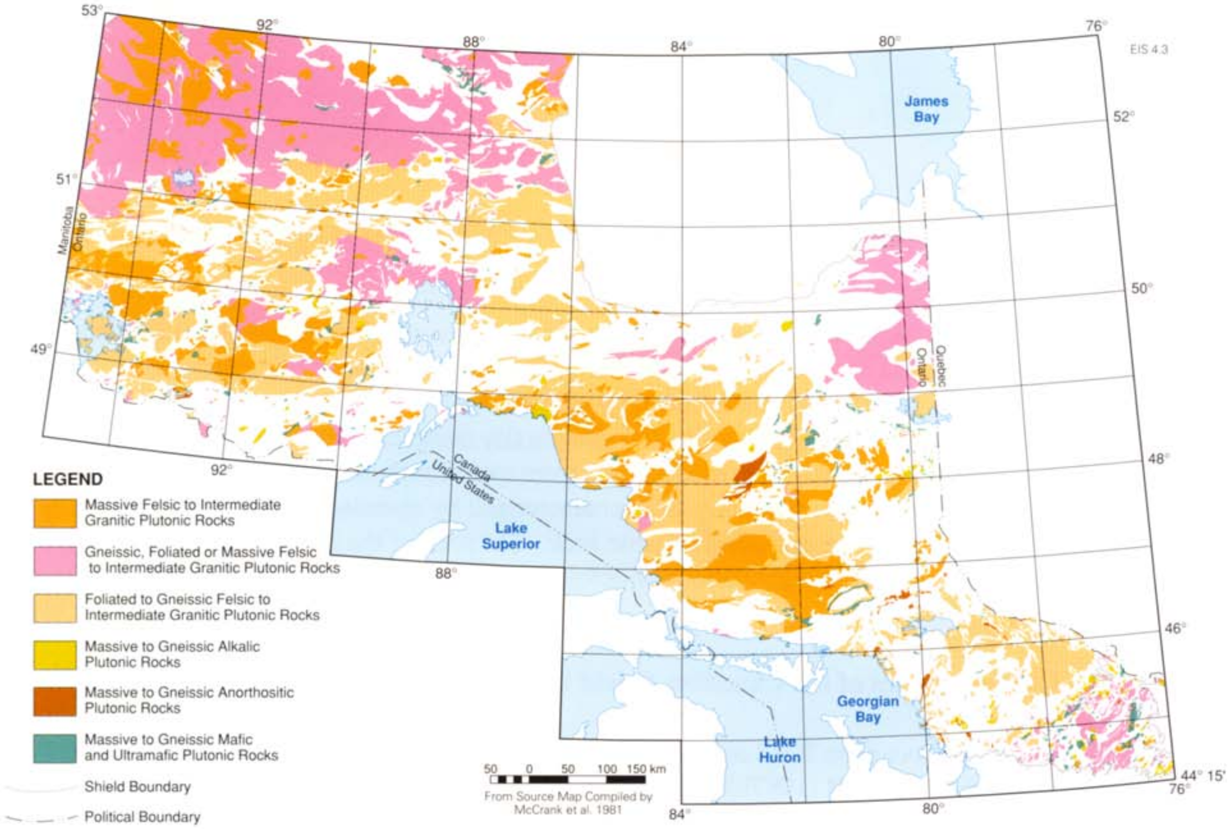

Figure 6: Distribution of plutonic rock in Ontario (AECL, 1994, Figure 4-3, page 98)

2.3 ALTERNATIVES TO PLUTONIC ROCK

The use of bedded salt formations and salt domes as possible sites of a HLRWM facility has been extensively explored in the United States. The greatest body of literature and experience relates to the U.S. Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP) facility near Carlsbad, New Mexico. The site, located in a Permian-age bedded salt deposit 658 meters below the surface, serves as a geological repository for selected defense-related transuranic radioactive waste. On March 26, 1999, WIPP received its first shipment of waste from the Los Alamos National Laboratory after DOE demonstrated compliance with all applicable regulatory requirements. Other candidate salt sites that have been studied by the US DOE include bedded sites in the Permian Basin, Texas (Stone and Webster, 1983) and Paradox Basin, Utah (Woodward Clyde Consutants, 1984) and the Vacherie Dome in Louisiana (Law Engineering Testing Company, 1982a) and the Richton Dome in Mississippi (Law Engineering Testing Company, 1982b).

The characteristics of salt that are favourable for disposal are its low water content, low permeability, high thermal conductivity and ability to undergo plastic deformation. The plastic deformation allows a degree of self-sealing in a repository. However, in Ontario, the occurrence of salt formations is rather limited as compared to the occurrence of plutonic rock formations. Further limiting the potential use of the salt sites in Ontario for a HLRWM facility is the fact that the salt at these sites has an economic value and the sites are located in areas of higher population than most plutonic rock areas (AECL, 1994).

Shale formations also have the potential for a HLRWM facility. While the shale formations in Ontario occur over a larger portion of the province than do the bedded salt sites (refer to Figure 4), the most readily accessible formations are found in the more populated areas and often occur in sedimentary sequences that contain oil, gas and coal deposits (AECL, 1994). The characteristics of shale that are favourable for a waste disposal facility are low permeability, high sorption capacity and ease of excavation. Beneath the Bruce Nuclear Power Development on Lake Huron, the Ordovician shales of the Michigan Basin are likely to have hydraulic conductivities in the range of 10^{-11} to 10^{-14} m/s at depths of 500 m (Moltyaner et al., 1995). The porewater in the formation is highly saline and stagnant. However, the physical properties of shale can undergo significant irreversible alteration with low or moderate changes in moisture, temperature, or stress; the extent of these changes is different for shales of different composition (AECL, 1994). There is a great variation in the texture, mineralogy, degree of lamination and degree of compaction of different shale formations.

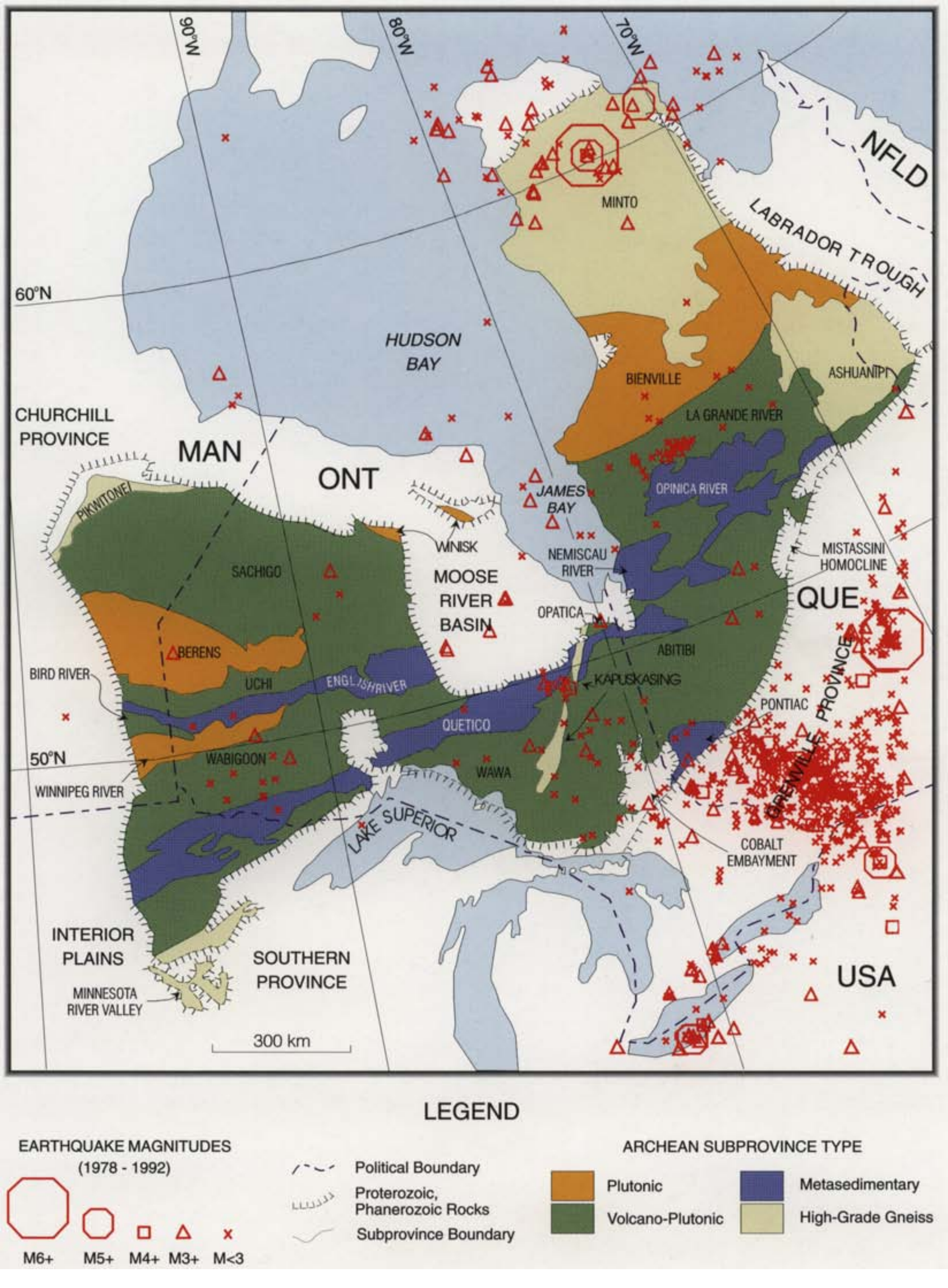

Figure 7: Seismicity on the Canadian Shield (Davison et al., 1994, Figure 2.6.1, page 47)

2.4 THE ONTARIO SETTING

Ontario is the largest producer of HLRW in Canada and while there are numerous locations throughout the country that may be suitable candidate sites for a deep geologic repository, it is probable that sites in Ontario would be considered for the first national facility. The geologic attributes of the potential sites within Ontario that lead to this conclusion include the areal extent of plutonic rock, the large regions of low seismic activity, the low geo-economic potential of large sections of the Shield and paleoclimate considerations. The last factor is important as it relates to the fact that there will be minimal biosphere impact in the regions above a repository during glaciation (refer to Section 2.5).

The management and visualization of geographic data that are important in candidate site selection, characterization and assessment has been facilitated in recent years by the use of Geographical Information Systems (GIS). Digital data that are readily available include bedrock geology (Figure 8), quaternary geology (Figure 9) and surface topography using a Digital Elevation Model (DEM) that provides estimates of the elevation of the ground surface. Visual inspection of the bedrock geology of Ontario (Figure 8) obtained from the 1:1,000,000 Ontario Geological Survey map shows that the geology of the Province is relatively well defined and dominated by the crystalline rock of the Canadian Shield. The mottled areas in the figure are predominantly the Shield areas while the sedimentary bedrock formations in Southern Ontario and the Hudson Bay region have a more uniform and layered appearance in the figure. The geology supports the conclusion that large areas of crystalline bedrock rock of the same type occur in the more seismicly stable western part of the province; the dominant rock type is massive to foliated grandorite to granite. Smaller areas of potassium feldspar megacystic units and foliated to massive tonalite to granodiorite respectively are also present. The quaternary or surficial geology (Figure 9) for much of the shield area of the province is granite with only small areas of till occurring.

A deep geologic repository is optimally located in areas with low horizontal hydraulic gradients with these regions more likely occurring in regions of low topographic relief. The topographic map of Figure 10 shows that large sections of the Shield have a relatively flat regional gradient of less than 0.002 m/m. These low gradients coupled with the low permeability of the deeper crystalline rock increase the likelihood of sluggish or stagnant porewater occurring at deep repository depths.

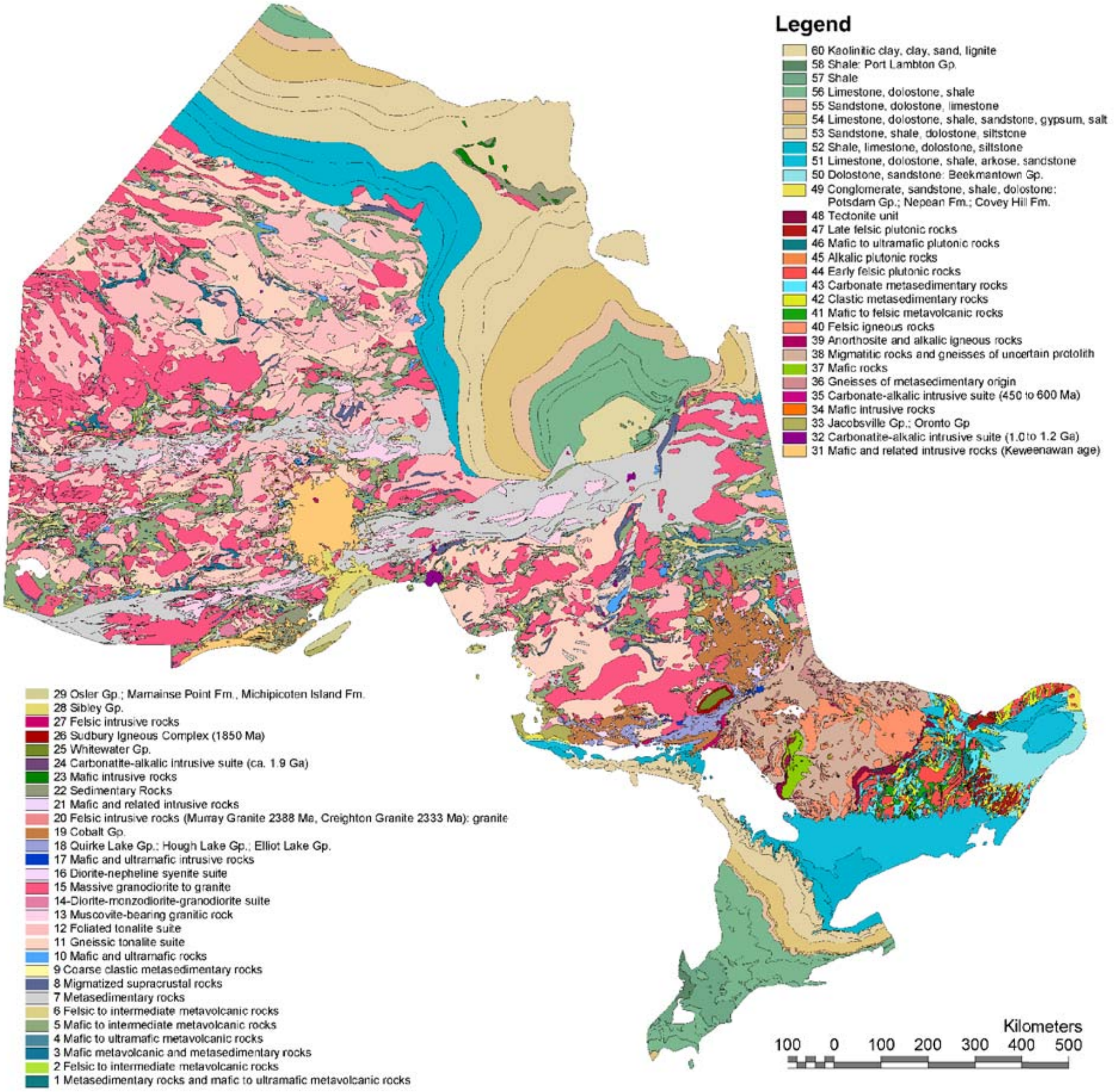

Figure 8: Ontario bedrock geology

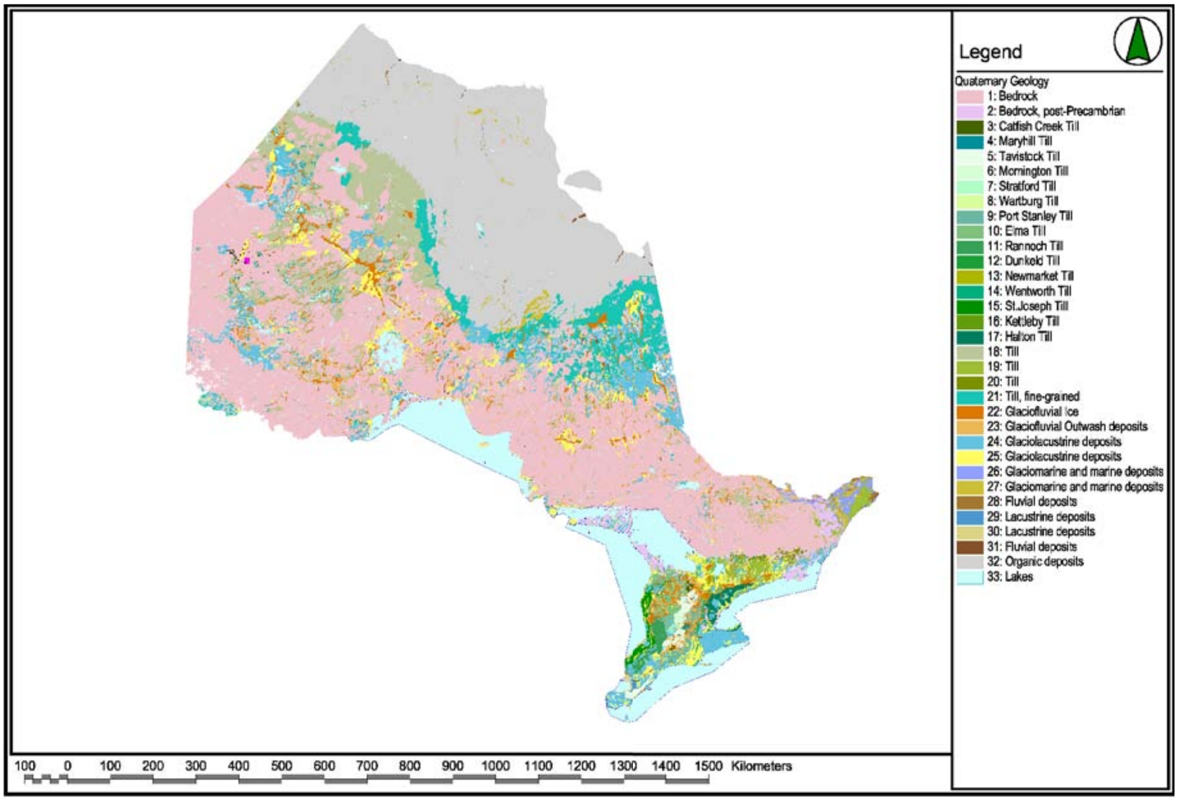

Figure 9: Quaternary geology for Ontario

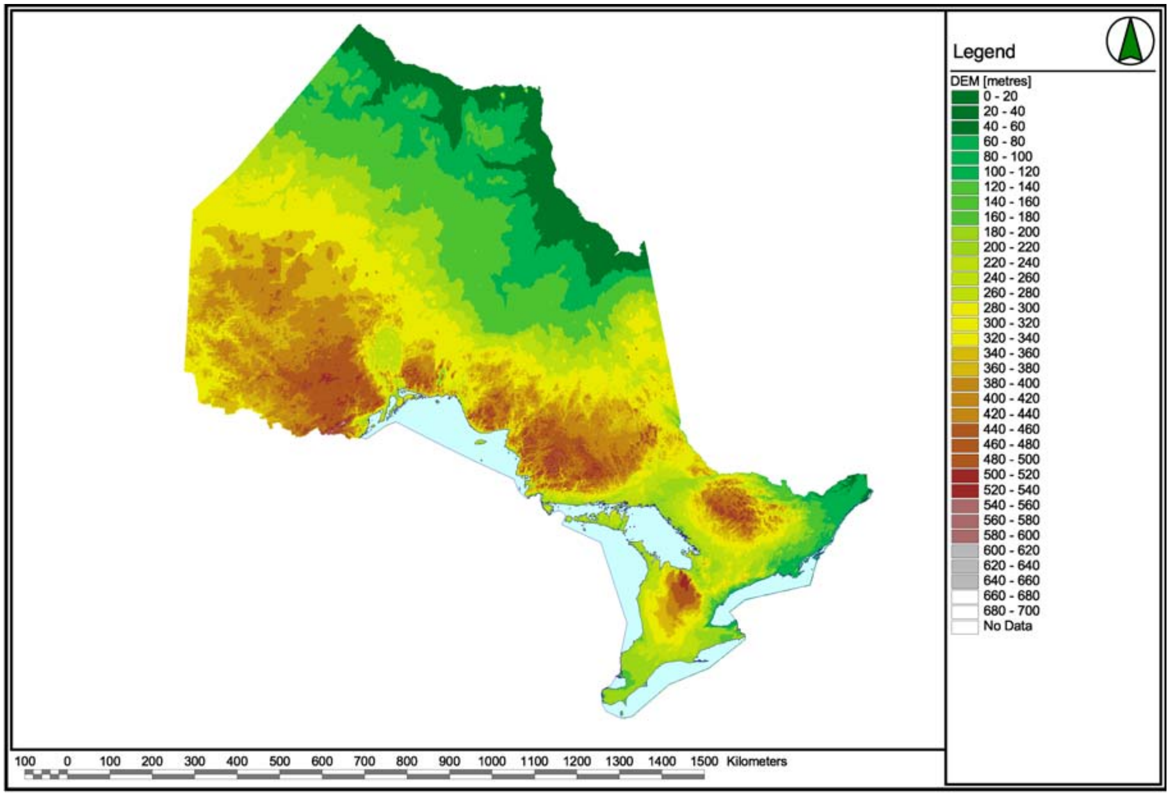

Figure 10: Topography for Ontario

2.5 GEOSPHERE EVOLUTION: PALEOCLIMATE

Peltier (2003) states that

> "the glaciation-deglaciation cycle of the late Quaternary period is a global phenomenon, but one that has exerted its most profound influence upon the Canadian portion of the North American continent. Nine times in the past 900,000 years, this region has become heavily glaciated with the thickness of the dominant Laurentide ice-sheet reaching upwards of 4 km in its primary domes. In each 100,000 year cycle of glaciation and deglaciation the buildup to maximum ice cover has occurred relatively slowly over a timescale of 90,000 years whereas the retreat phase has been relatively rapid, lasting approximately 10,000 years. The phenomenon is known to have occurred as a consequence of variations in the effective intensity of the Sun at the position of the Earth due to the action of gravitational n-body effects in the solar system that are responsible for causing quasi-periodic changes in the geometry of Earth's orbit. The volume of ice that accumulates upon the polar continents during each glacial cycle has been such as to cause global sea level to fall by approximately 130 m at each maximum of glaciation. The phenomenon may be most usefully thought of as constituting a highly nonlinear forced oscillation of the global hydrological cycle.
>
> There currently exists a theory of this nonlinear hydrological oscillation which predicts its observed timescale and temporal structure as well as the geographical regions that become covered by ice at each time of glacial maximum (e.g. see Peltier 1998 for a review). Of considerable current interest are the regional characteristics of the glaciation-deglaciation process predicted by the theory for the North American continent. Especially important are the variations of ice-thickness at glacial maximum as a function of geographic position. Very recently (Peltier, 2002), it has been shown that the Laurentide Ice Sheet at Last Glacial Maximum must have assumed a multi-domed form with the greatest thickness of ice existing over the Keewatin sector of the Canadian Shield centered in the vicinity of Yellowknife.
>
> As this ice sheet retreats, extensive pro-glacial lakes are known to have formed adjacent to the retreating ice-margin, lakes whose positions are predicted by the theory and which have left an unmistakable imprint upon the landscape that may be compared to model results. The timing and routing of the drainage of these lakes into the sea has profound consequences for the global climate variations that are known to have occurred during the deglaciation process."

Therefore, scientific evidence indicates that this hydrological cycle will continue and that an ice-sheet will again cover the Canadian Shield for most of the next 100,000 years. Safety assessment must consider the presence of the ice cover in the calculation of the impact of leached waste from a failed repository canister migrating through a crystalline rock geosphere to a biosphere similar to that existing today in central Antarctica.

As a result of the last glacial episode, the land surface of the Canadian Shield in Ontario is currently rising slowly as a result of the melting and retreat about 10,000 years ago of the Laurentide Ice Sheet. During glaciation, the surface was depressed due to the mass of the overlying ice. The rate of rebound decreases with time, but it is still over 6m/1000 years (0.6 cm/year) around Hudson Bay. The rate of rebound declines with distance away from Hudson Bay and approaches zero at the southern edge of the shield (Davison et al., 1994, pg 36). Additional impacts of ice-sheet growth on the Canadian Shield are a change in the thermal regime of the geosphere including pore water freezing in the shallower rock and the mechanical loading of the geosphere due to the mass of the overlying ice. This surface loading will change hydraulic gradients and result in increased pore and rock pressures at repository depths. The signature of the increased pressures that occurred in the last glacial period can be measured today in deep observation boreholes in the Canadian Shield.

2.6 GROUNDWATER MOVEMENT

The correlation between topography and groundwater flow patterns has been investigated in several crystalline rock settings. The analysis of water levels in boreholes at the Aspo Finland hard rock laboratory (Stanfors et al., 1999) indicates that the undisturbed water table approximately follows the topography and that the annual fluctuation in the water table is greater for areas near surface water divides, for example at topographic high points, than for areas close to the zones where groundwater discharges to streams. It was observed that the surface of the water table is locally very irregular because the hydraulically active fractures are sparsely distributed and not well interconnected hydraulically. At depth, the irregular pressure distribution becomes smoother and probably, to a large extent, becomes governed by the fracture zones and large fractures with high transmissivities. Similar observations were made at the WRA (Stanchell et al., 1996)

In subsurface systems in which gravity is the dominant driving force for water movement, groundwater flow patterns are generated by the topography of the watershed and modified by the spatial variations in the permeability of the subsurface lithologic units, by the presence of faults and fracture zones, and by density differences in the groundwater. In general, for watersheds in the Canadian Shield, recharge and downward groundwater movement occurs at topographically high regions, upward groundwater flow and discharge occurs at topographic depressions such as stream valleys or lake basins, and groundwater through-flow that is sub-parallel to the land surface occurs under medium elevations between mounds and vales (Toth and Sheng, 1996).

The groundwater flow in watershed scale systems has been characterized using three different orders: local, intermediate and regional (Toth, 1963). The flow is termed local if the recharge and discharge areas are contiguous. The flow system is intermediate if it does not occupy the main divide and valley bottom and if the recharge and discharge areas are separated by one or more local systems. The groundwater flow is regional if it links hydraulically the crest and bottom of the watershed.

Toth and Sheng (1996) argue that watershed scale or basinal groundwater flow can be exploited to maximize the time of travel of average water particles from a deep storage or disposal vault to the surface. They put forth the argument that “basinal groundwater flow is the single most crucial technical question in ensuring the safety of geologic disposal, that a robust hydrogeological model can be developed on the basis of this understanding, and that such a model is amenable to meaningful assessment". In their Recharge Area Concept, they postulate that theoretical situations with subsurface hydraulic characteristics that meet regulatory requirements a priori can be produced and then a search undertaken for a real site that matches the critical aspects of the modeled flow field. (Toth and Sheng, 1996). A formulation of the major procedural stages of repository-site selection based on the Recharge Area Concept is developed from two premises: 1) regional recharge areas are preferable to other parts of drainage basins in Canadian-Shield type environments, and 2) groundwater flow in a Shield-type area is controlled by the topographic relief. Regional groundwater flow can, therefore, be exploited to enhance the role (utility) of the geosphere as a barrier to radioactive-waste migration by judiciously selecting the basin and placing the storage or disposal vault near the basin's crest where regional recharge occurs (Toth and Sheng, 1996).

To validate the theory put forth by the Recharge Area Concept, Toth and Sheng (1996) modeled steady-state saturated groundwater flow in hypothetical cross-sections that were 20 km in length and 4 km in depth. The cross-section was assumed to represent one flank of a centrally symmetrical depression or one side of a river valley. The water table at the basin crest was set to be 400 m higher than the river elevation at the valley floor and a sine wave was used to represent the configuration of the water table. Their work investigated the travel paths through a hypothetical repository located at different locations in the cross-section for various conceptualizations of the subsurface permeability or hydraulic conductivity distribution and fault zone configuration. The idealized cross-section was comprised of three stratigraphic layers: a 300 m thick layer below the water table, a 1700 m thick mid layer and a 2000 m thick deep layer. Hydraulic conductivities for the layers ranged from 10^{-9} m/sec to 10^{-11} m/sec (corresponding permeabilities are 10^{-16} m^2 to 10^{-18} m^2). The sensitivity was investigated for the average water particle travel time to the presence of a single fault at various dips and two different anchor depths. Based on the analysis, it was concluded that regional groundwater recharge areas occur and that these areas are the preferred location for a waste repository. However, this conclusion is subject to several limitations. The analysis did not include the occurrence of higher density pore waters at depth as have been observed in the Canadian Shield. The analysis did not include the effect of elevated heads at lower depths on the groundwater flow field. Most importantly, the conclusion is based on the analysis of steady-state groundwater flow in an idealized cross-section rather than groundwater flow in three-dimensional watersheds with actual Canadian topography.

Three-dimensional modeling of groundwater flow in crystalline rock at the regional scale and sub-regional scale was undertaken for both the EIS and the SCS (see Sections 3.3 and 3.4 of this report). The domain and conceptual model for the analyses was based on the data for the WRA and the location of the hypothetical repository corresponds approximately to the location of the URL. The hypothesis of the Recharge Area Concept is that the optimal location of a used fuel repository is one that maximizes the time of travel of average water particles from the domain of the vault to the biosphere and that this location is most likely to occur in a regional groundwater recharge area. Based on the Concept, the location of the hypothetical disposal vault in both the EIS and the SCS may not be optimal. The vault location for both studies was determined by the presence of sparsely fractured rock and a waste exclusion zone with sufficient extent to accommodate the footprint of the hypothetical repository or vault. Whether the location was in a regional groundwater recharge area as defined by the Concept was not an a-priori constraint or factor. For the Recharge Area Concept to considered or become a potentially binding constraint on locating a used fuel repository, it must be evaluated in the context of the three-dimensional groundwater flow in watersheds with all of the attributes of the watershed being considered. These attributes include actual surface topography from Canadian Shield watersheds as compared to data for two-dimensional generic cross-sections as used by Toth and Sheng (1996), the inclusion of brines in the deeper rock and their effect on pore water density, the inclusion of elevated anomalous heads in the deeper rock, the use of permeability versus depth models that appropriately reflect measurements that have been made for crystalline rock settings in the Canadian Shield, and the complex intersection of fracture zones.

The recent work of Sykes et al. (2003), refer to Section 3.5, has shown that regional scale flow does not likely occur in watersheds on the Canadian Shield. With appropriate permeability versus depth models, the low topographic relief of the shield coupled with the complex surface water system results in groundwater flow paths occurring only at the sub-regional and smaller scales. The selection of a site for of a deep geologic disposal or storage vault should be influenced more by the location of sub-regional scale fracture zones and by geochemistry factors than by the recharge area concept.

3. THE CANADIAN DEEP GEOLOGIC RESEARCH PROGRAM

3.1 GEOSPHERE AT THE WRA

AECL's Whiteshell Research Area (WRA) is located near Lac du Bonnet, Manitoba. The Underground Research Area (URL) is within the area. The WRA includes a substantive portion of the Lac du Bonnet Batholith (refer to Figure 11) with this being a large granitic rock body several kilometers deep with an exposed surface measuring over 60 km long and 20 km across at its widest point. The Batholith was intruded over 2.5 billion years ago into the rocks existing at the time and is comprised of several plutonic intrusions. The main intrusion is grey granite that contains pink porphyritic granite at its upper surface. The lineaments or observed surface traces of bedrock joints, fracture zones and dykes have been mapped at the WRA.

Within the regional domain depicted in Figure 11, the Winnipeg River stretches from the topographic low of 285 m below the Pointe du Bois dam to 255 m at Lac du Bonnet. The water table in the WRA is a subdued replica of the topographic surface; water table highs are more likely to occur at topographic highs while water table lows are more likely to occur at topographic lows and the location of the water table tends to follow surface topography. Therefore, the water table divides roughly correspond with the surface water catchment boundaries. The elevations of the water table at the regional divides are up to 50 m higher than at the regional lows. Depth to the water table is up to 15 m in upland areas with a seasonal fluctuation from 4 to 6 m. In low-lying areas, the water table is 1 to 2 m below the ground surface with a seasonal fluctuation of less than 1 m. Water table slopes in the URL upland areas range up to 0.04 while the regional slopes range up to 0.004 averaging 0.002. Numerous small creeks and tributaries of the Winnipeg River drain the WRA. Over much of the eastern part of the WRA, granitic and gneissic rock crop out at ground surface. In the western part of the area, most of the bedrock has a soil cover that ranges up to 30 m thick. The surficial soils are silty clays or clays and in low lying areas they can be overlain by a thin layer of organic soil over a silty to sandy till that is up to 3 m thick. Fractures occur sporadically in the till and clay soils.

On the basis of frequency and spacing of open fractures, the rock is characterized into three domains (refer to Figure 12):

- A fracture zone (FZ), which is a volume of intensely fractured rock;
- Moderately fractured rock (MFR) zone, which is a volume of rock containing a small number of sets of relatively widely spaced discrete open fractures; and
- Sparsely fractured rock (SFR), which is a volume of rock containing microcracks and very sparsely distributed open fractures that as a rule are not interconnected.

The fracture zones are the major structural features controlling groundwater movement in plutonic rock bodies (Davison et al., 1994, pg 105, 106).

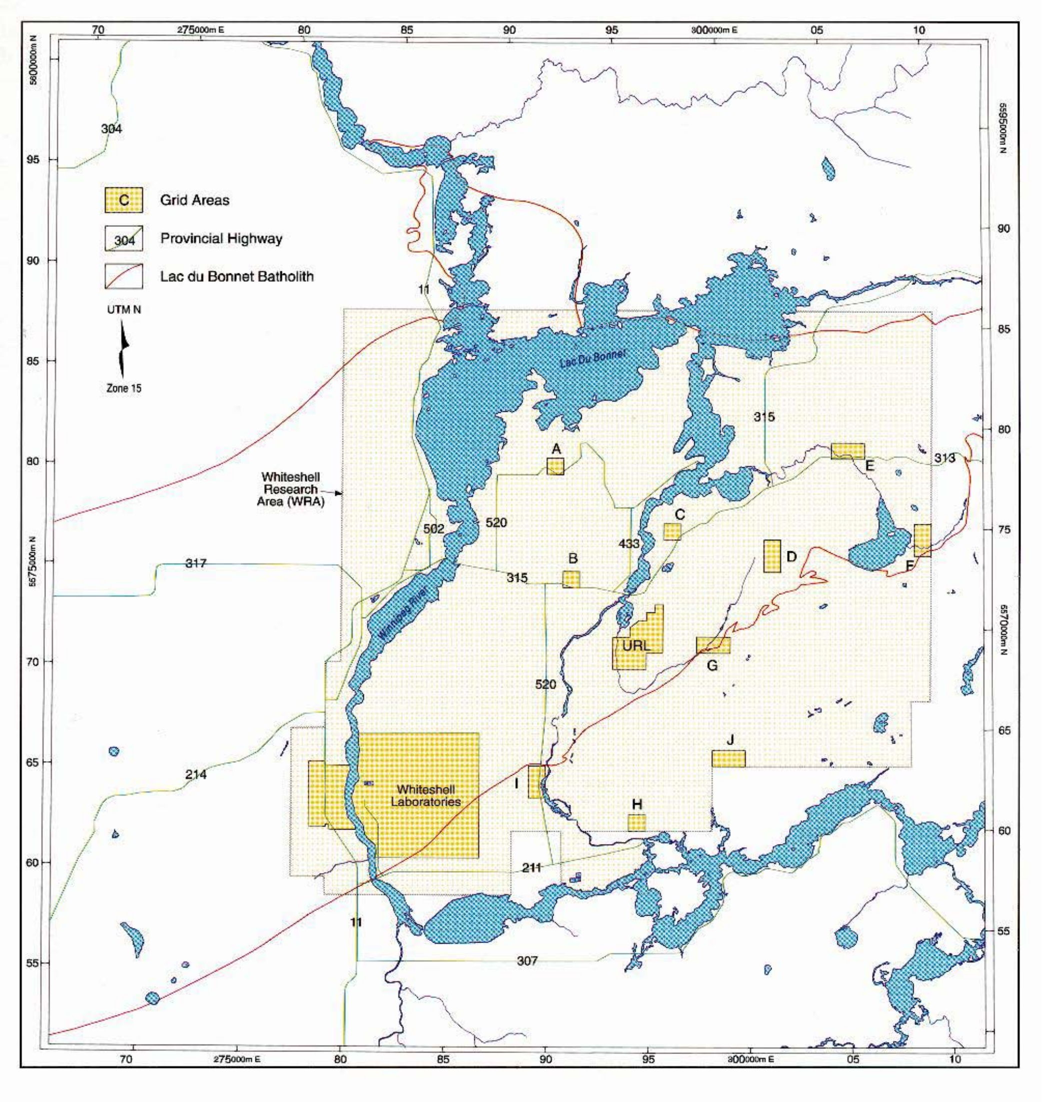

Figure 11: The Whiteshell Research Area And Underground Research Labratory

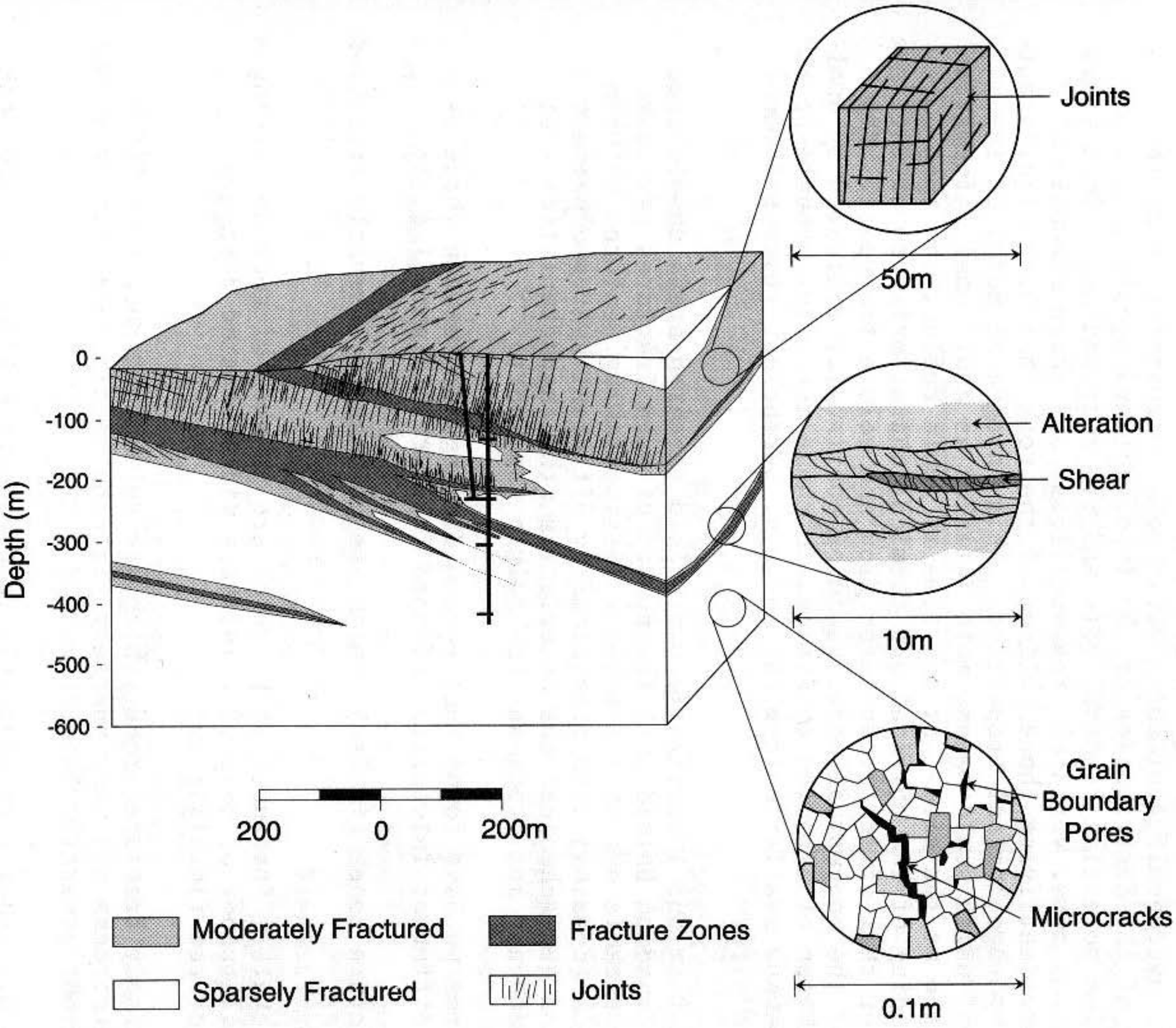

Figure 12: Cross section at URL

The fracture distribution and hydraulic characteristics of the Batholith at the WRA have been determined using data from a network of boreholes. Most of the major fracture zones (FZ) were intersected within 300 m of ground surface and have a low to intermediate dip. The average geometric mean thickness of the FZs is 3 m. While some boreholes intersected FZs at depths between 500 m and 1000 m. It was concluded that these FZs have limited extent and were bounded by less permeable rock. The regions of MFR were observed mostly within 300 m of the surface. Below a depth of 300 m, regions of MFR occur adjacent to fracture zones. Most boreholes at the WRA intersected large volumes of SFR. The depth to the top of the zones that had a thickness greater than 300 m ranged from 100 m to over a 1000 m. The massive volumes of SFR generally occur below the more-shallow regions of FZ and MFR. The SFR consists of a relatively thin upper layer of pink granite where it occurs at shallow depths and at deeper depths it is a thick volume of grey granite. The pore water in the grey granite at a depth of 420 m in the

URL has a dissolved mineral content ranging up to 90 g/L consisting of mostly $CaCl_2$, and has a residence time of 10^7 to 10^9 years. Anomalously high environmental hydraulic heads relative to the water table elevation have been observed in some test intervals in the SFR. It is postulated that the elevated anomalous heads in the SFR are a result of past glaciations coupled with the high porewater salinity. The data support the conclusion that the SFR has a very low permeability and that the pore fluids are largely stagnant over periods of more than 10^6 years

Investigations of the crystalline rock at the URL are being undertaken at all spatial scales and all rock domains. For SFR, radionuclide migration is dominated by diffusion. However, fluid flow caused by pressure gradients (advection) can occur in rock fractures thereby increasing the potential for radionuclide migration. The theory of fracture flow is understood. Ongoing experiments by OPG and AECL are being undertaken to further improve the modeling and prediction of flow and radionuclide migration in fractures. Tracer tests in MFR at the URL have also been undertaken. Work to determine the MFR hydraulic parameters and transport parameters using the tracer data is yielding excellent results (Park et al., 2003).

Figure 13: Quarried block experiment – separation of the URL quarried block (OPG annual report 2002, figure 9, page 18)

At a larger scale, hydraulic tests and interference tests in the boreholes show that the FZs in the upper 300 m at the WRA are interconnected and behave as a hydraulic continuum. Hydraulic heads in the intervals were estimated using measured pressure and salinity data for the interval. The hydraulic heads in the intervals that span the shallower portions (< 100 m) of the FZ and MFR respond rapidly to the seasonal changes in groundwater recharge. This rapid response corresponds to low storativity, a function of the rock and water compressibility, high hydraulic conductivity and good connectivity in the shallow, fractured rock networks. The groundwater in most shallow boreholes is fresh. For the SFR, the radius of influence of the hydraulic tests was a fraction of metre and no permeability anisotropy (ratio of horizontal to vertical permeability) was reported. In general, the results of the tests indicate a decrease in permeability with depth for the domains of FZs, MFR and SFR at the WRA. For the FZs, the permeability ranges from 7.5 × 10^{-19} m^2 to 1 × 10^{-13} m^2. The range in permeability for the MFR was from 6 × 10^{-18} m^2 to 1 × 10^{-15} m^2 while for the SFR the permeability ranged from 1 × 10^{-21} m^2 to 7.7 × 10^{-19} m^2 (Stevenson et al., 1996). Based on field tracer tests, the connected porosity of the FZ was estimated to range from 0.02 to 0.42. For the MFR and SFR, representative porosities range from 0.005 in the upper 1000 m of the Batholith to 0.001 at depths greater than 3200 m (Stevenson et al., 1996).

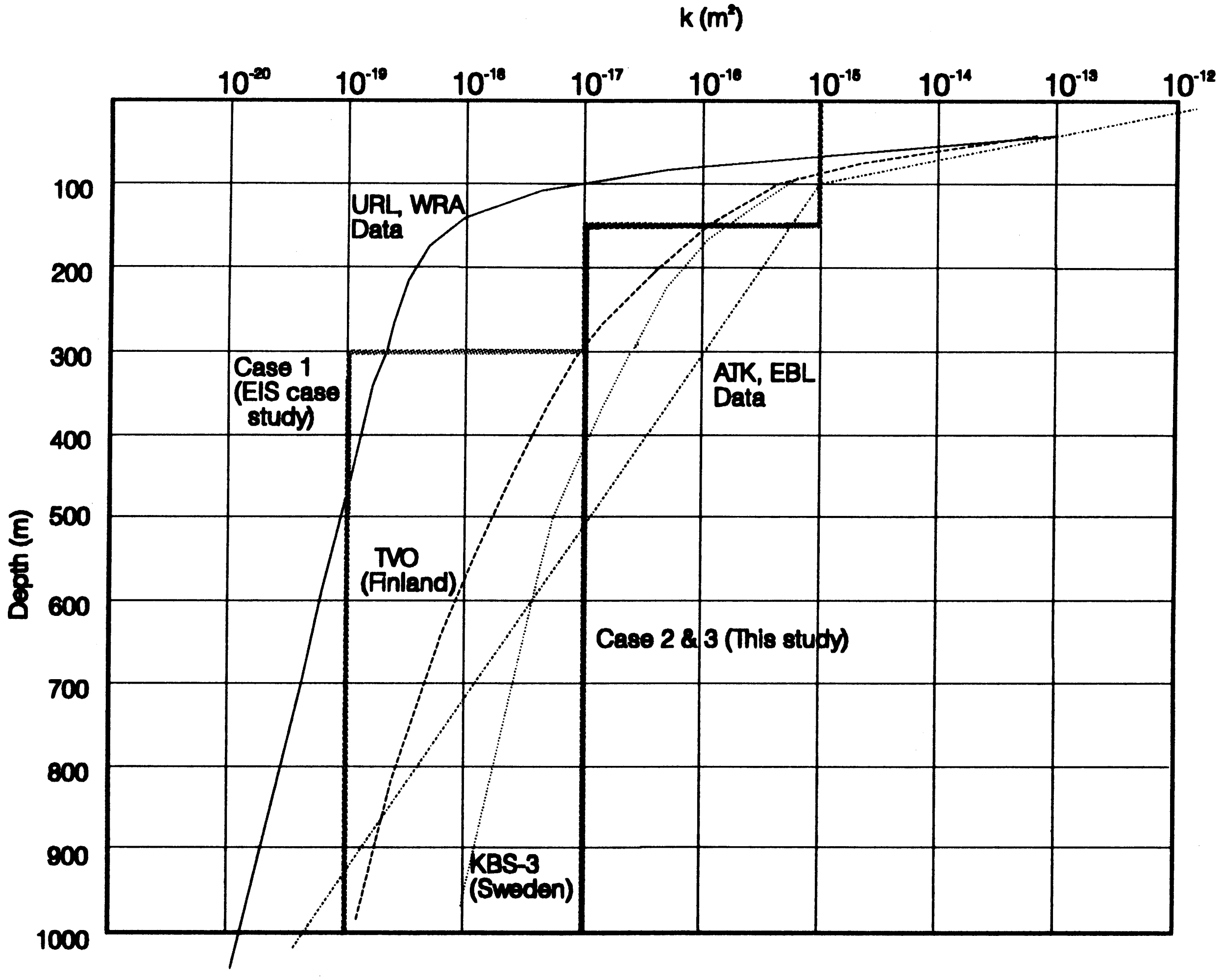

Figure 14: Permeability versus depth at the URL and data from the Swedish and Finnish Assessments of Fennoscandian Shield Conditions (from Stanchell et al., 1996, Figure 3; note that "this study" refers to the SCS)

The variation of the measured permeability with depth at the URL is shown in Figure 14. The permeability for crystalline rock in Finland and Sweden are also shown. Finally, the figure presents the data used in the conceptual model for the EIS and the data used for the SCS (referred to as "this study" in the figure). At repository depths, the SCS model significantly overestimates the permeability of the rock as compared to that measured in the URL, Finnish and Swedish studies. This overestimation will result in a very conservative safety assessment. A schematic diagram of the permeability, porosity and saline distributions of the revised conceptual model for the URL (from Stevenson et al., 1996) is shown in Figure 15.

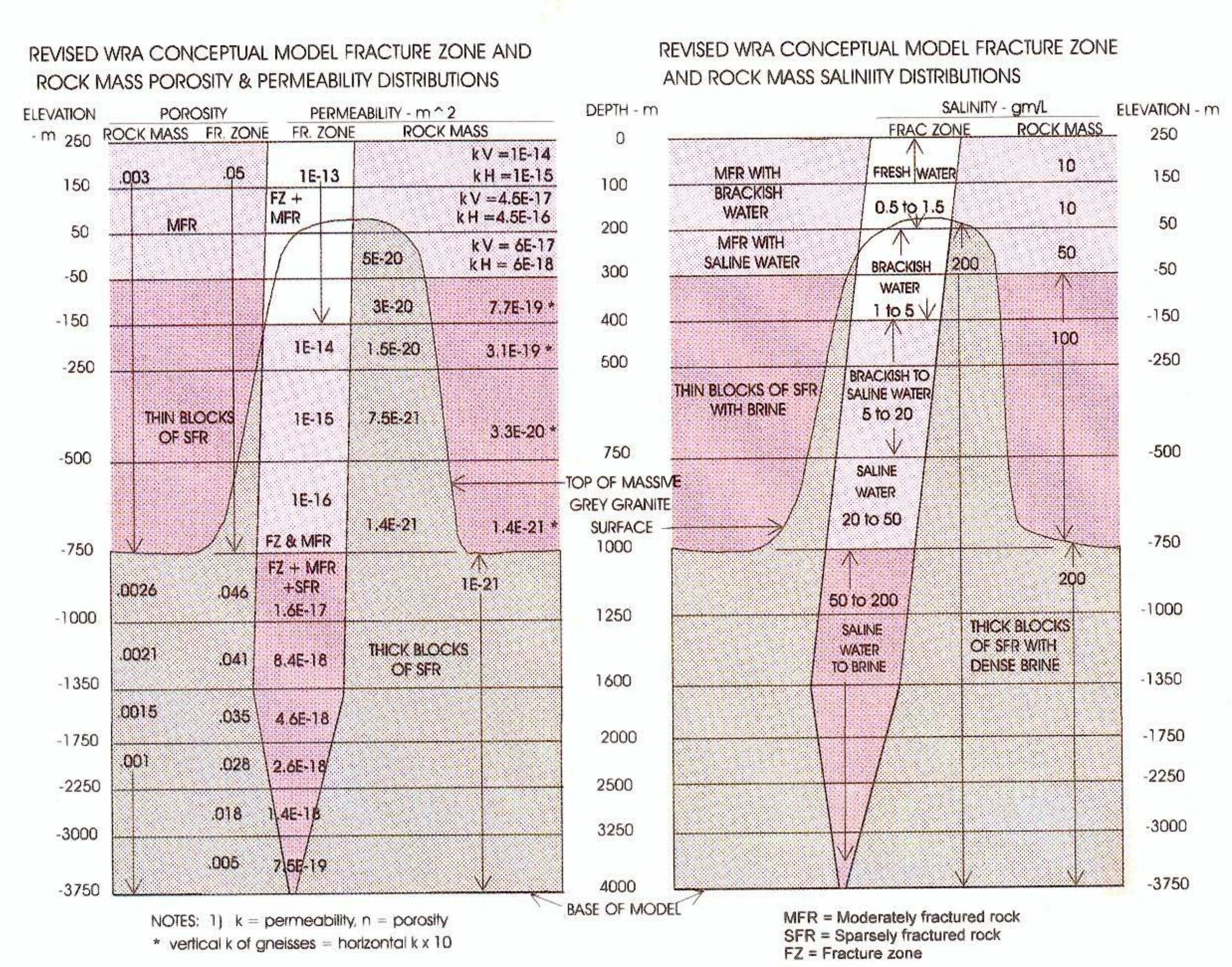

Figure 15: A schematic section of the permeability, porosity and salinity distributions in the revised conceptual hydrogeologic model (Stevenson et al., 1996, figure 12, page 29)

3.2 GEOCHEMISTRY

The geosphere performs a number of functions relevant to long-term security and safety of a HLRWM facility, one of the most important being the provision of a chemical environment that provides a range of geochemical immobilization and retardation processes, favours the long-term stability of the engineered barriers and is itself stable due to a range of chemical buffering reactions. The salinity of groundwater in plutonic rock on the Canadian Shield generally increases with increasing depth. Salinity and chloride data for borehole WB-1 at the WRA URL are shown in Figure 16 while the variation in salinity with depth using data from all bedrock groundwater at the URL is shown in Figure 17 (from Gascoyne, 2000). The data support the conclusion that the water at repository depths is likely to be highly saline. This fact is important as the fluid density is related to the salinity (Figure 18) and higher density groundwater will tend to move more sluggishly than less dense water.

Two theories have been postulated to explain the presence of the highly saline groundwater in the deeper rock. Salinity may have originated from groundwater recharge during episodes of marine intrusion. Alternatively, the salinity may be a result of rock-water interactions. Shallow recharging groundwater typically has a low content of dissolved solids and is of a calcium bicarbonate composition. With the slow movement of the infiltrating water through fractures, surfaces of open fractures are altered to clay minerals and calcium carbonate is precipitated. Over thousands of years, the water becomes rich in chloride and sulphate ions (Davison et al., 1994, pg 107). The change in the sulphate concentration and bicarbonate concentration with depth in the granitic rock using all of the groundwater data at the URL is shown in Figures 19 and 20 respectively (from Gascoyne, 2000). The concentration versus depth relationships show strong trends for both species with the SO^4 increasing with depth and the HCO^3 decreasing with depth.

At repository depths of 500 m to 1000m below the surface, a reducing condition exists in the water in the fractures and rock matrix (Davison et al., 1994, pg 107). The relationship between redox potential (measured as Eh using an electrode sensor) with depth at the URL is given in Figure 21 (from Gascoyne, 2000). The general trend is a decrease in Eh with depth.

The tritium (^3H) content of the groundwater in plutonic rock can be used with other isotopic data to determine the age of the water. The change in ^3H concentration with depth at the URL is given in Figure 22. The concentrations of isotopes in the shallow near surface groundwater indicate that the porewater has had a relatively short residence time in the flow system and most infiltrated within the last 50 years (Gascoyne, 2000). The water in the upper 200 m of bedrock contains active groundwater in the vertical and low-angle fracture zones with residence times of 10 to 1000 years. At depths from 200 to 400 m the isotopic signature suggests the residence time of the groundwater is from 1000 to 100,000 years. Below 400 m the groundwater in fractures is saline and is pre-glacial in origin with residence times of over 1,000,000 years. In the deeper SFR, data support residence times of at least 10,000,000 years (Gascoyne, 2000).

A schematic diagram showing the generalized evolution of the groundwater at the URL is shown in Figure 23. Gascoyne (2000) states that the almost universal observation of low Br/Cl ratios and high $\delta^{34}S$ values of the dissolved SO_4 indicates that the salinity of most of the fracture groundwaters and the pore fluids is derived from a marine source likely as a result of infiltration during early Paleozoic times. The hydrogeochemical data indicate that below 500 m at the URL, fracture hosted groundwaters are very saline, reducing, and old. The groundwater can be considered as essentially stagnant over the period of concern for a HLRWM facility (10^6 years).

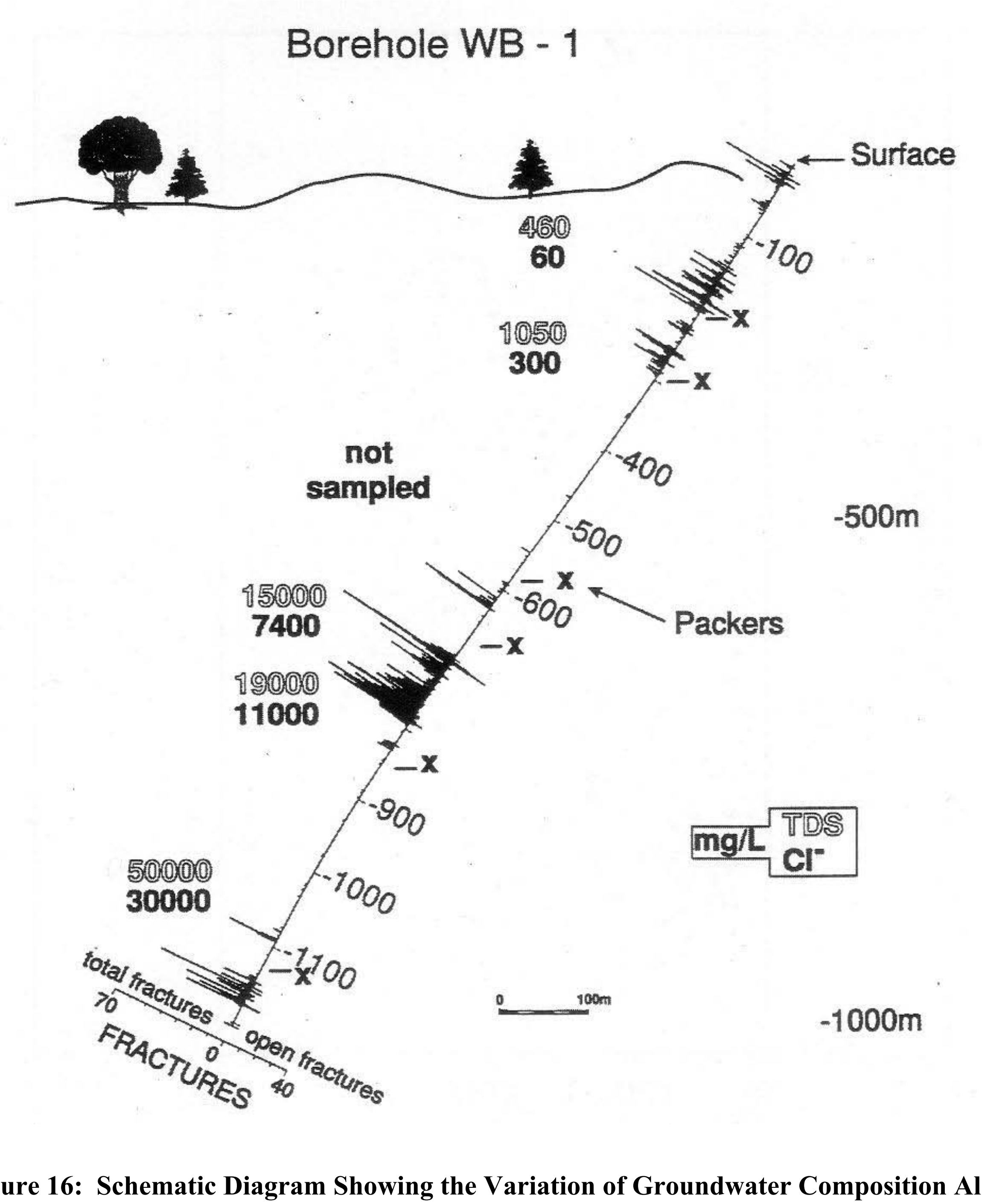

Figure 16: Schematic Diagram Showing the Variation of Groundwater Composition Along the Profile of Borehole WB1 at the WRA URL (from Gascoyne, 2000, Figure 12, page 69)

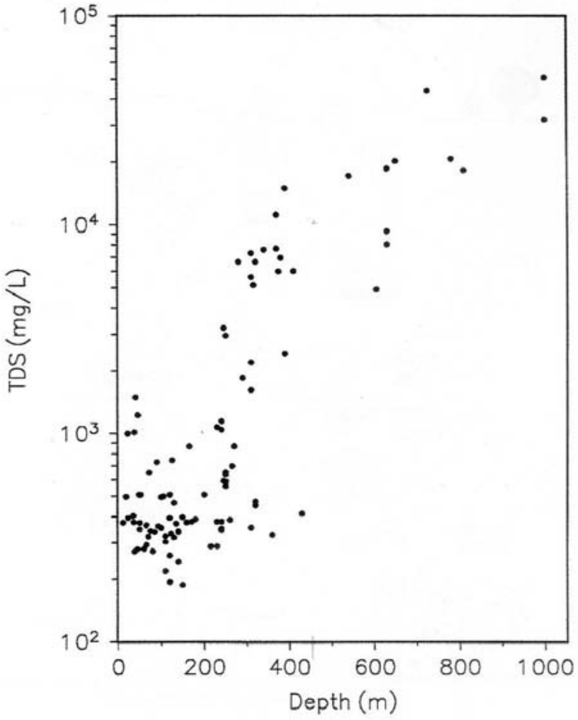

Figure 17: Variations of Salinity (as TDS) Concentrations in Groundwater with vertical Depth (Gascoyne, 2000, Figure 13a, page 70)

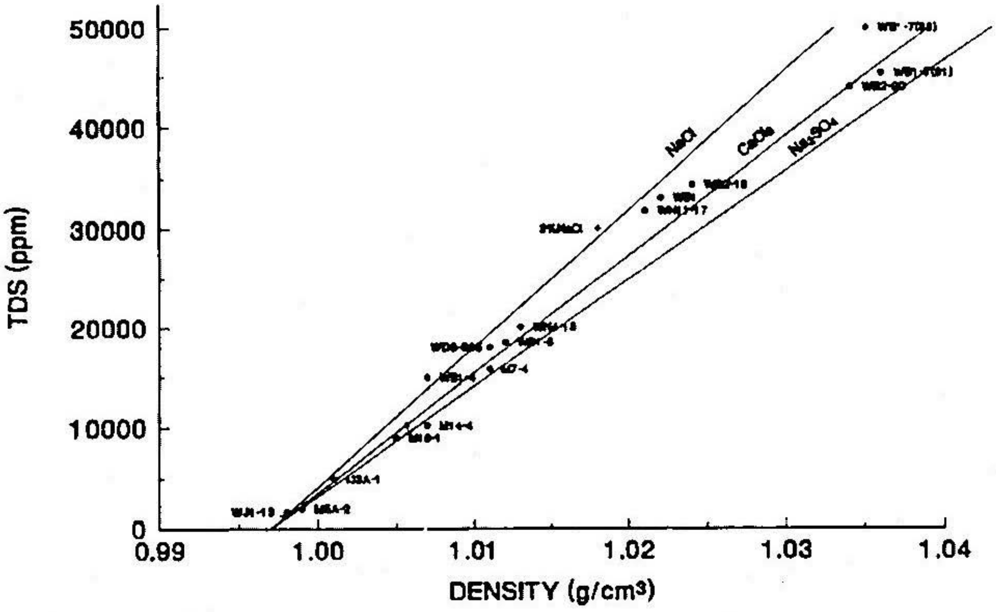

Figure 18: Relationship between density and salinity (as TDS) for Brackish and Saline Groundwaters, Compared with that of Synthetic Solutions. (Gascoyne, 2000, Figure 15, page 81)

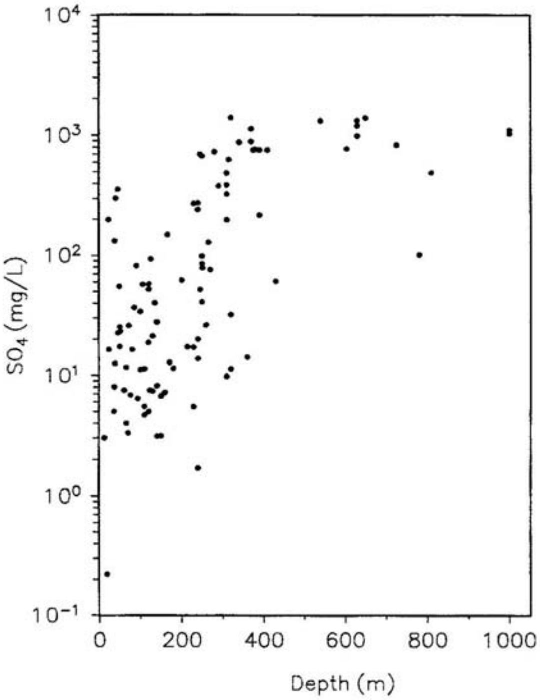

Figure 19: Variations of SO_4 Concentrations in Groundwater with vertical Depth (Gascoyne, 2000, Figure 13e, page 74)

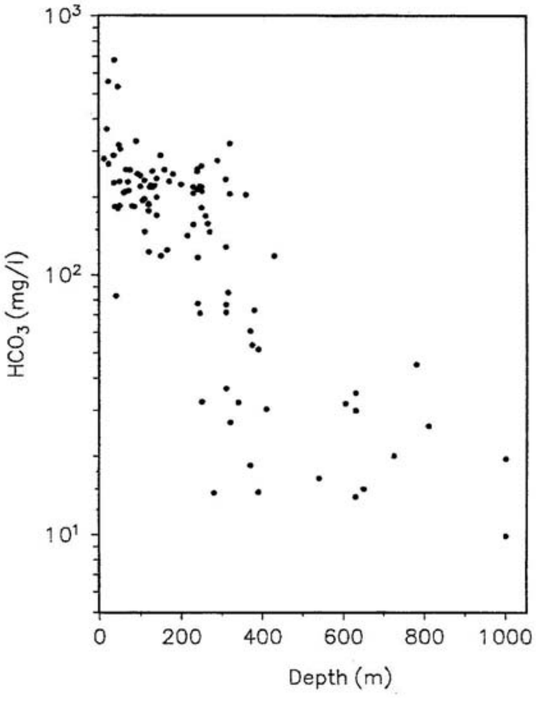

Figure 20: Variations of HCO_3 Concentrations in Groundwater with vertical Depth (Gascoyne, 2000, Figure 13a, page 70)

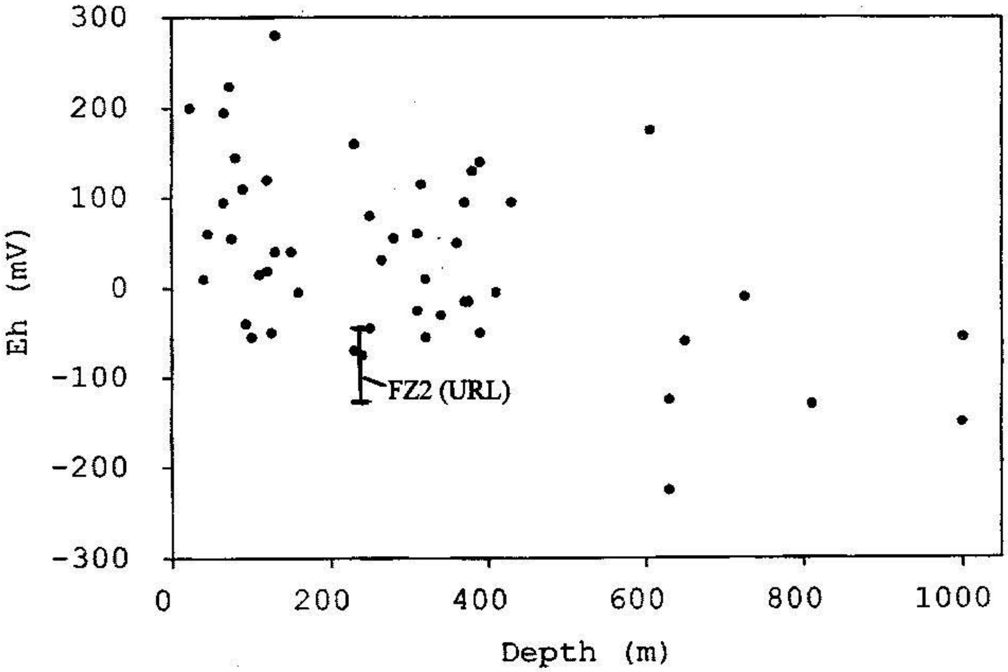

Figure 21: Variation of Eh with depth (Gascoyne, 2000, Figure 22b, page 104)

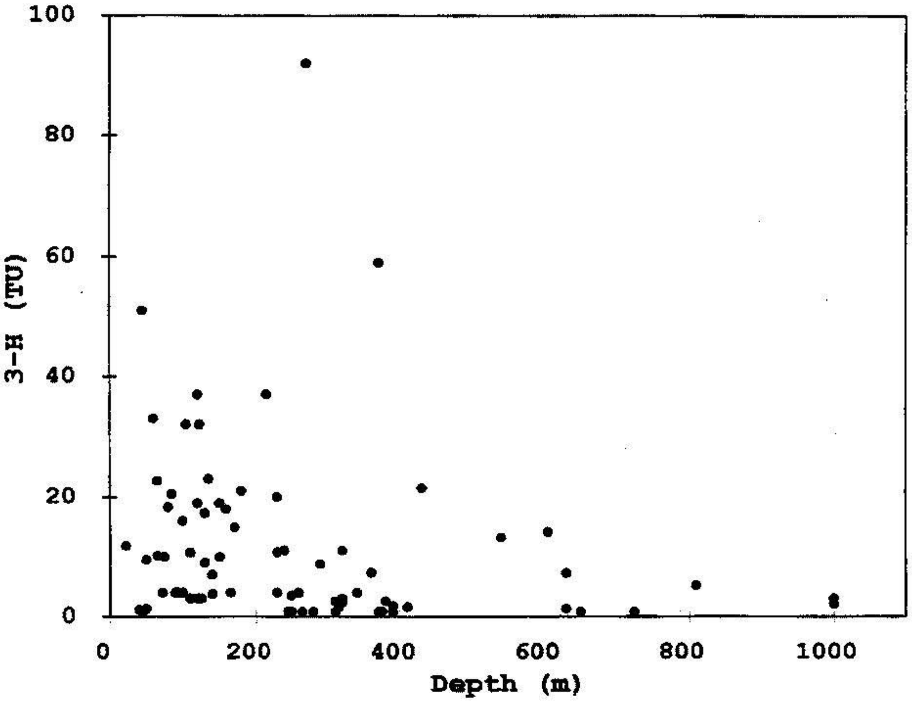

Figure 22: Variation of ^{3}H with Depth (Gascoyne, 2000, Figure 23a, page 105)

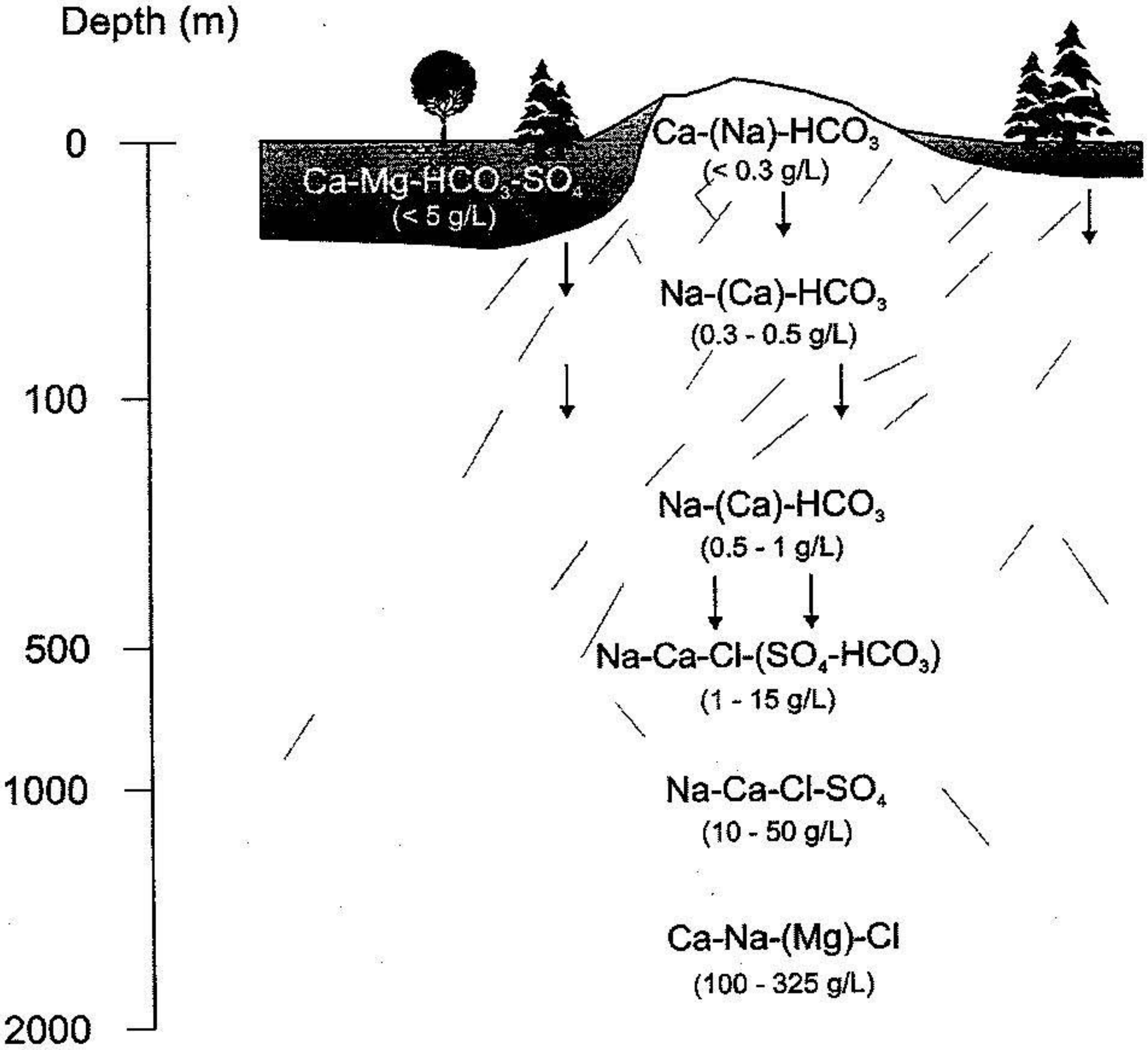

Figure 23: Schematic Diagram showing the Generalized Evolution of Composition and Salinity of Groundwater with Depth in the Lac du Bonnet Granite (Gascoyne, 2000, Figure 28, page 114)

3.3 THE CASE STUDY OF THE ENVIRONMMENTAL IMPACT STATEMENT

The Environmental Impact Statement (EIS) describes a case study of the long-term performance of a hypothetical implementation of a reference disposal system (Davison et al., 1994). The geological characteristics of the reference geosphere were derived from data from the extensive laboratory, field and engineering investigations at the WRA. The hypothetical vault was located at a depth of 500 m in sparsely fractured rock.

Three-dimensional modeling was undertaken for the validation of the finite element groundwater model MOTIF (Davison et al., 1994). The regional scale domain for these analyses extended to a depth of 1.6 km and included three-dimensional finite elements representing the low permeability, low porosity MFR and SFR rock mass. Two-dimensional planar elements were used to represent the thin layer of surficial soils, an identified fracture zone at the location of the Whiteshell Laboratories site, and the three fracture zones identified at the URL site (FZ1, FZ2 and FZ3). For the rock mass, the horizontal hydraulic conductivity was assumed to be uniform and varied from 10^{-12} m/s at a depth of 1000 m below sea level to 10^{-7} m/s at the surface. The hydraulic conductivity for the FZs were assumed to be uniform at 10^{-6} m/s.

Three-dimensional simulations were also undertaken to investigate the effects of the extent of the spatial domain on local scale processes, to examine the influence of pumping groundwater from a domestic groundwater supply well and to identify the specific discharge areas to the biosphere for groundwater that has passed through the hypothetical vault. The three-dimensional modeling was developed at two scales: a regional scale and a local scale or sub-regional scale. The spatial domain for the regional scale modeling encompassed an area bounded by the Winnipeg River that is approximately 33.2 km by 25.6 km. The domain extended to a depth of 4 km and included the equivalent porous media rock mass representing the MFR and SFR. Fracture zones were simulated as two-dimensional planar features. No-flow boundary conditions were used for the bottom and sides of the regional flow domain while prescribed head values equal to the surface topography were used for the top boundary.

The spatial domain for the three-dimensional local or sub-regional scale modeling encompassed an area of 10 km by 9 km centered on the URL and extended to a depth of 1.5 km. The boundary conditions for the upper surface of the model were prescribed heads equal to surface topography. The side and bottom boundary conditions were obtained from the regional scale analysis. Three-dimensional finite elements with an equivalent porous media assumption were used for the three rock domains of FZ, MFR and SFR. The properties for this rock mass were assigned to represent the presence of FZ, MFR or SFR. The permeability of the SFR surrounding the vault was 10^{-19} m^2 with an effective transport porosity of 3×10^{-3}. The analyses in the EIS ignored the impact of brine concentration on pore water density.

3.4 SECOND CASE STUDY

The Second Case Study (SCS) illustrated the potential of designing the engineered barriers and the vault to increase the robustness of the long-term safety case to compensate for hydrogeological conditions that could result in a less than effective geosphere barrier than the one specified for the EIS case study. For the SCS, groundwater flow velocities through the geosphere surrounding the hypothetical disposal vault were estimated using the MOTIF three-dimensional finite element groundwater model (Davison et al., 1994). The assumed geographic setting of the sub-regional or local hydrogeological model is identical to that of the EIS case study and covered a 10 km by 9 km area of the WRA and extended to a depth of 1.5 km. The geometry of the FZ, MFR and SFR domains for the Second Case Study are identical to those used for the EIS case study and the hypothetical disposal vault is located at a depth of 500 m at the same geometric location with respect to the fracture zones and rock domains. The spatial domain was vertically discretized using three equivalent porous media layers. The top two layers (from ground surface to a depth of 300 m) were assigned anisotropic permeabilities and to reflect the average effect of systematic subvertical fractures that are observed in the shallow WRA, the vertical permeabilities were assigned values equal to five times the horizontal permeability. Layer 3, extending from 300 m to a depth of 1.5 km was assigned an isotropic permeability of 10^{-17} m^2 with an effective transport or connected porosity of 10^{-3} to 10^{-5}. Major fracture zones were included as discrete equivalent porous media features with an assumed uniform thickness of 20 m, a longitudinal permeability of 10^{-13} m^2 and a porosity of 10^{-2}. The boundary conditions for the analyses of the SCS were Dirichlet with an assigned head equal to the topography on the top surface and no-flow on the domain sides and bottom.

3.5 THE DEEP GEOLOGIC REPOSITORY TECHNOLOGY PROGRAM

There is significant ongoing work by OPG, AECL and their consultants on the Deep Geologic Repository Technology Program (DGRTP). Whereas the EIS and SCS were largely the work product of AECL, the DGRTP integrates work by a broad range of scientific and engineering experts in consulting firms, private corporations and universities. The safety assessment and site characterization work in the DGRTP is using a new generation of tools for world-leading analyses. A significant aspect of the DGRTP is the closer integration of site characterization and safety assessment. The lack of integration in the EIS (Davison et al., 1994) was identified as a weakness by the SRG (1995). The current research activities in the DGRTP as listed in Jensen and Vorauer (2003) are summarized in Table 1 of this report. Details of the activities are contained in the DGRTP annual reports (OPG, 2001; OPG., 2002; OPG, 2003)

To demonstrate the concept for HLRWM in a deep geologic setting, a numerical analysis of a 5734 km^2 watershed situated on the Canadian Shield has been conducted to illustrate aspects of regional scale groundwater flow within a typical Shield setting (Sykes et al., 2003). The modelling strategy adopted a GIS framework that included a Digital Elevation Model (DEM) and surface hydrology features such as rivers, lakes and wetlands. Model boundary conditions were extracted through GIS automation from the surface hydrology features. At the regional scale, the post-glacial evolution of the groundwater flow system was investigated using the Equivalent Porous Medium (EPM) finite difference model SWIFT-III in which the fluid density and viscosity are fully dependent on the fluid pressure, temperature and groundwater salinity. The finite element model FRAC3DVS was also used to simulate the same regional scale groundwater flow system. Various results from FRAC3DVS were compared to those from SWIFT-III. With a discretization of over 1.5 million grid blocks, the 1.5 km thick spatial domain was used to explore the sensitivity of groundwater flow to topography, variable matrix permeability distribution models, pore water salinity and the dissipation of elevated initial pore pressures that result from ice that overlaid the watershed in the last glacial period.

Steady-state analyses indicate that piezometric head in all model layers are highly correlated to surface topography. A series of transient analyses provide evidence that for horizons greater than 600 m depth, the low permeability (10^{-19}-10^{-17} m^2) of the granitic rock coupled with saline pore water creates a sluggish flow system in which mass transport may be diffusion dominated. Denser pore waters due to salinity can affect average water particle paths and induce density gradients that can enhance or reduce topographically driven gradients. Robustness in groundwater flow simulations due to variations or uncertainty in the spatial distribution of matrix permeability is assessed. Numerical evidence further suggests the existence of long-term pressure head transients resulting from dissipation of glaciation induced flow system perturbations. Further work is planned to better assess the development and behaviour of increased pressures at depth due to glaciation events. Simplifying and possibly conflicting assumptions required of models with reduced physical dimensionality are not necessary as the three-dimensional nature of topography, surface water features, and the spatial variation of matrix permeability have all been natively incorporated within SWIFT-III and FRAC3DVS. In fact, groundwater flow interpretations that are based on simplified models may yield physically implausible results.

A detailed groundwater flow analysis of a 100 km^2 portion (refer to Figure 24a) of the larger regional 5734 km^2 watershed situated on the Canadian Shield has been conducted to illustrate aspects of regional and sub-regional groundwater flow that are relevant to the long-term performance of a hypothetical nuclear fuel repository (Normani et al., 2003). The discrete-fracture dual continuum finite element model FRAC3DVS was used to investigate the importance of large-scale fracture networks on flow and particle migration. Various GIS data sources were used to facilitate the development of the sub-regional model: Digital Elevation Model (DEM) with a planimetric resolution of 3 arc seconds and a vertical resolution of 1.0 m; Digital NTS (National Topographic Service) maps at a scale of 1:50,000 to represent contours, lakes, rivers, wetlands, dams, and other features found on the NTS maps; and Aerial photography at a scale of 1:60,000 from the National Air Photo Library (NAPL). The aerial photography was digitized, orthorectified, and mosaiced to the Digital NTS GIS files, as shown in Figure 24a.

For modeling, surface water features such as wetlands, lakes and rivers are defined as Dirichlet (Type I) boundary conditions. The Digital Elevation Model (DEM) was used to establish the elevation of these water features, and consequently the top layer of the numerical model. A recharge boundary condition (Type II or Neumann) was not used to represent infiltration from precipitation for the top surface of the model, but rather the Dirichlet boundary condition of fixed piezometric head was applied. This application is based on the fact that the water table is typically a subdued representation of surface topography. The northern model boundary was chosen based on a topographic divide, while the eastern, southern, and western model boundaries were chosen coincident with rivers. An implied assumption from the use of rivers as model boundaries is that water does not underflow these rivers. This conclusion is supported by the regional scale analyses.

Table 1: Summary of DGRTP Geoscience Work Program Activities

	Geoscience Work Program	Program Description
1	Long-Term Climate Change	A climate driven and geophysical constrained Laurentide ice-sheet model consistent with the last Laurentide glacial cycle (121 kBP - present)
2	PERMAFROST Case Study	A joint international research project investigating the influence of permafrost on groundwater flow system evolution in a continuous permafrost crystalline rock setting (i.e. Lupin Mine Nunavut).
3	WRA Hydrogeochemical Case Study	A compendium and synthesis of hydrogeochemical data gathered within the Whiteshell Research Area relevant to site-specific groundwater flow system evolution and dynamics.
4	WRA Fracture Mineral Infill Case Study	A paleohydrogeologic study of fracture infill mineralogy and isotopic composition within the Lac du Bonnet batholith as related to the evolution of fracture fluid compositions and the depth of penetration by low-salinity oxygenated glacial recharge.
5	Regional Shield Groundwater Flow System Analysis	A reasoned 3-dimensional numerical analysis (FRAC3DVS/ HydroSphere) of a 5700 km^2 that is examining the influence of flow system dimensionality, spatial permeability distributions, discrete fracture network interconnectivity, salinity and transient long-term boundary conditions on Shield flow system hydrodynamic and geochemical stability.
6	WRA Lineament Analysis Case Study	An interpretative and systematic GIS based lineament analysis of the WRA using historic and remotely sensed data sets.
7	3D Discrete Fracture Network Modelling	A geostatistical approach for the development of field constrained and geologically reasoned 3-dimensional discrete fracture network models.
8	Thermodynamic Modelling – Glacial Recharge	An insight modelling study using the Thermodynamic code PHREEQC to assess the role of Fe-bearing minerals in maintaining poised redox conditions within the felsic Lac du Bonnet batholith – specific emphasis on influence of possible oxygenated glacial recharge to repository horizons.
9	Reactive Transport Modelling - State-of-Science Review	A review of the current status and applicability of reactive transport codes for prediction of geochemical evolution and porosity-permeability feedback within the geosphere (and engineered barrier systems) – specific focus on mineral and biological mechanisms affecting redox stability.
10	Moderately Fractured Rock Experiment	A series of forced gradient tracer tests to explore the applicability of the Equivalent Porous Media approximation for simulation of solute transport in a fracture network at scales of 10 to 50 m. Comprises the MFR Modelling Task Force (3 research teams) .
11	In-situ Diffusion Experiment	A series of comparative steady-state laboratory diffusion cell and in-situ field experiments to assess the effect of scale dependency, mineralogy, rock texture, stress, temperature, anisotropy and fracture mineralization on estimated effective diffusion coefficients.
12	Quarried Block Experiment	A series of flow and tracer experiments and accompanying numerical simulation within a single (variable aperture) 1 m^2 fracture plane.
13	Hydraulic Well Test Analysis – nSIGHTS	An application of numerical methods for the analysis of transient flow and pressure well bore tests in deriving estimates of T and S in intact and moderately fractured granitic rock.
14	Canadian Shield Seismic Activity Monitoring	A continuation of low-level seismic activity monitoring in Northern Ontario with a 12 station seismograph network.
15	Apatite Fission Track Thermochronology	An international collaborative study of Apatite Fission Track Thermochronology as relevant to Canadian Shield tectonics and fracture generation/history.
16	Virtual Reality Theatre - Data Synthesis/ Interpretation.	A test-pilot project to assess the applicability and utility of Virtual Reality technology for the integration of complex multi-disciplinary geoscientific data sets relevant to the development of a descriptive conceptual geosphere model for the Moderately Fractured Rock Experiment.
17	DECOVALEX III	An international forum in which coupled Thermal-Hydraulic-Mechanical codes are being applied to geoscience issues of; i) repository re-saturation; ii) field parameter homogenization/up-scaling; and iii) glaciation as it affects repository and flow system stability.

The aerial photography served as the basis for developing a complex irregular Discrete-Fracture Network (DFN) model that was superimposed onto the finite element flow domain mesh. . A surface lineament analysis was conducted by Srivastava (2002) to define the major fracture features. These fracture features are mainly coincident with surface drainage features that exhibit linearity. Additional surface lineaments were created to account for the extension of existing major lineaments, and to increase the fracture density in areas where overburden cover would have obscured the surface lineaments or where the aerial photograph had weak contrast, such as the southern third of the image (see Figure 24a). The resulting surface fracture features are shown in Figure 24a. This fracture generation procedure preserves both the fracture orientation and fracture length distribution statistics.

The surface traces are then propagated to depth until one of the following conditions are met:

- the fracture's down-dip width reaches a prescribed length to width ratio;
- the fracture truncates against an existing fracture;
- the fracture reaches the edge or bottom of the modelled domain.

Horizontal fracture intersections at various depths are shown in Figure 24a. As can be seen, fracture density decreases with increasing depth; minor fracture features are more shallow than the major fracture features. The resulting discrete fracture network contains a high degree of realism that honours many geological, statistical, and geomechanical constraints (Srivastava, 2002). A three-dimensional view of the discrete fracture network is shown in Figure 24b. The crystalline rock between these structural discontinuities was assigned properties characteristic of those reported for the Canadian Shield.

The existence of large-scale fractures is a significant contributor to the dissipation of residual pore pressures resulting from ice that overlaid the watershed during the last glacial period. These pressure transients can influence the migration of average water particles since a particle's movement may not be dominated by topographic relief, but rather by the presence of a nearby fracture. Interconnectivity of permeable fracture features is an important pathway for the relatively rapid migration of average water particles and subsequent reduction in residence times. The presence of high salinity pore waters further perturbs the direction and magnitude of flow in the deeper rock. As geological data become available from field site characterization activities, the robustness of flow simulation outcomes can be assessed on an on-going basis by the use of geostatistical methods that honour the source data. As more field data such as pore fluid chemistry, in-situ rock stress, fracture geometry and interpreted permeability are incorporated within the flow model, uncertainty analyses can be used to more efficiently direct further field activities, by gathering data that will best aid in reducing the uncertainties determined in the flow model.

In summary, a much more detailed geosphere study of a hypothetical Canadian Shield like setting was performed. The use of realistic topography, delineation of fracture networks through air-photo interpretation that honours many geological, statistical, and geomechanical constraints, and the use of fine discretization grids have exceeded the previous studies of a similar nature.

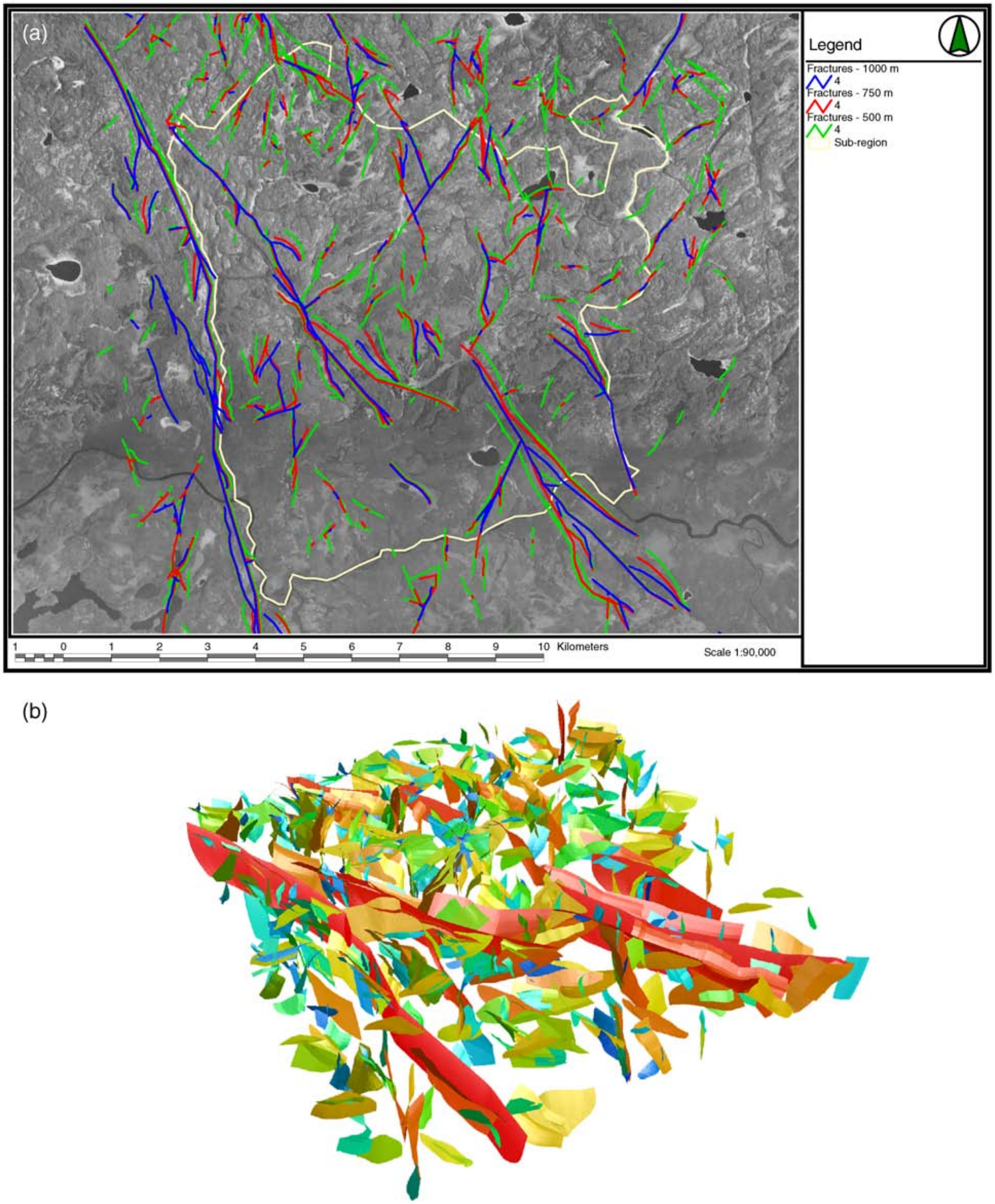

Figure 24: Domain for sub-region analysis (a) Ortho-photo showing fracture lineaments, and (b) isometric view of the generated three-dimensional discrete fracture zones

3.6 SUMMARY OF GEOSPHERE SETTING AND VAULT DESIGN

Attributes of the Canadian Shield geosphere setting and vault design concept are as follows:

- For safety assessments, the most important failure is expected to be due to pinhole failures of cannisters. However, cases with large area failure may be considered as well.
- Containers may be placed in either an in-floor configuration or an in-room configuration.
- The cavities in the vault that surround the containers are filled with compacted buffer and backfill. Although the material properties of the buffer and backfill are designed to be homogenous, especially after resaturation, there may be some spatial variation.
- As a result of the construction of the vault, an excavation damage zone of varying thickness and spatially varying rock properties surrounds the vault. The permeability of the EDZ is greater than that of the surrounding intact rock.
- The rock surrounding the vault and EDZ has spatially varying fracture frequencies and spatially varying properties.
- The groundwater in the rock fractures and matrix may have a total dissolved solids concentration that significantly impacts the fluid density.
- The vault may be located in a groundwater recharge zone, a groundwater discharge zone or a stagnant groundwater flow zone.
- Preferential paths for radionuclide transport may occur or develop through the buffer and backfill as a result of seal failure and spatially varying properties. Preferential paths may occur or develop in the EDZ and surrounding rock. Preferential paths may also occur in discrete fracture zones.

4. HLRWM CONCEPTS IN OTHER COUNTRIES

Countries such as Finland, Sweden and Switzerland are also considering the management of HLRW using a crystalline rock setting and a concept similar to that of Canada. Clay as a host for a potential deep waste vault is also being investigated in Switzerland. Ontario Power Generation has formal agreements with Sweden (SKB) and Finland (Posiva) to exchange information arising from their respective programs on nuclear waste management. Brief details of the concepts of these three countries are given in the following sections.

4.1.1 FINNISH CONCEPT

In the Finnish deep geologic repository concept (Vieno and Nordman, 1999), used fuel assemblies are placed in copper-shell canisters. Each canister has an integral cast iron component with holes for the emplacement of fuel assemblies. The canisters are to be placed in vertical holes bored in the floors of tunnels that are excavated at a depth of about 500 meters in crystalline bedrock (see Figure 25). The space between a canister and the rock will be filled with highly compacted bentonite. Tunnels and shafts will be backfilled with crushed rock and bentonite or with natural smectite clay. The corrosion lifetime of the copper shell canister in the expected repository conditions is predicted to be at least 100,000 years. The peak temperature at the canister-bentonite interface will be less than 100°C.

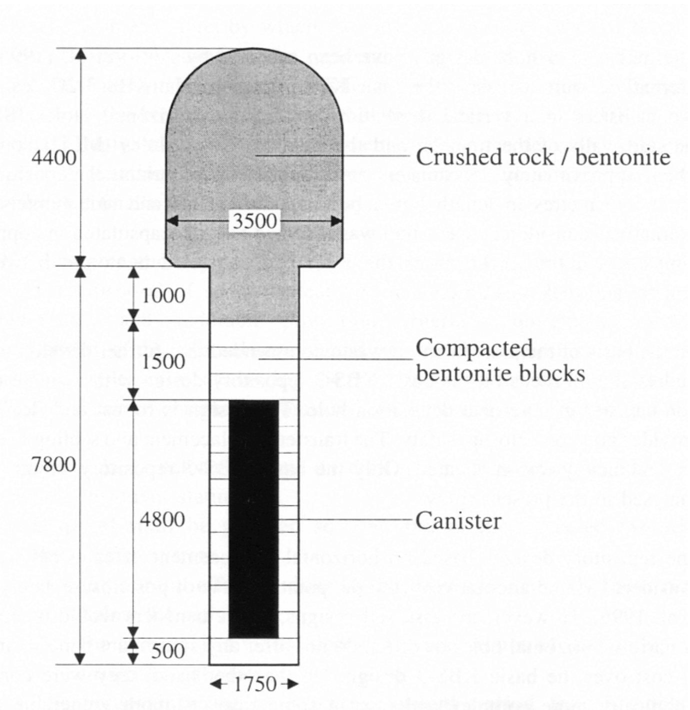

Figure 25: Deposition Hole for a Canister Containing Olkiluoto Fuel for Finnish Concept

Four candidate sites were considered for the Finnish used fuel: Romuvaara, Kivetty, Olkiluotto and Hastholmen. The characteristics of the rock at the sites were investigated, in part, using rock coring. The rock in which a vault will be constructed in the Finnish concept can be characterized as being fractured and having a spatially varying permeability (e.g., 2 to 4 fractures/m at Olkiluotto). The migration paths through the rock for radionuclides released from a canister consists of excavation damage zone, intact rock, fracture zones and combinations of them. Both upward and downward flow directions have been observed at the proposed vault elevations at the candidate sites. Depending on the site, the groundwater salinity varies. The groundwater at the Olkiluoto site varies from fresh at the surface to very saline at depth (69 g/L at a depth greater than 800 meters).

In the recent safety assessment of the Finnish concept (Vieno and Nordman 1999), it was assumed that radionuclides were released from a canister as a result of an undetected manufacturing defect. A disappearing (by corrosion) canister scenario was also considered.

4.1.2 SWEDISH CONCEPT

The Swedish concept for the disposal of used fuel (SKB, 1999) is to place the fuel in cast iron inserts that provide the necessary mechanical strength for corrosion-resistant copper-shell canisters. It is proposed that the canisters be placed in vertical holes in the floor of the vault.

The annulus between the canisters and the rock is to be filled with a layer of bentonite clay while the vault room is to be back-filled with a crushed rock (85%) and bentonite (15%) mixture. It is proposed that the vault be located at a depth of about 500 meters in crystalline bedrock. The excavation damage zone (EDZ) around a tunnel in the vault is approximately 0.3 meters thick on the top and sides while the floor thickness varies from 0.8 to 1.5 meters. The EDZ permeability is 1 to 2 orders of magnitude greater than that of the surrounding rock. The groundwater composition at the sites being considered for a repository is highly varying. The fracture frequency and the permeability of the rock at the candidate sites are spatially varying. The fractures occur on all scales from microscopic fractures in the rock matrix to fracture zones that have significantly elevated fracture frequencies in relation to the surrounding rock. Fracture zones often constitute dominant flow paths for the groundwater. In the recent safety assessment of the Swedish concept (SKB 1999), the most important scenario for radionuclide release was as a result of undetected defects in canisters.

4.1.3 SWISS CONCEPT

The first Swiss system proposed for the disposal of used fuel (Nagra, 1994) is to incorporate the high-level waste in a glass matrix that is encapsulated in a thin, stainless steel flask. The flask is then placed in a massive steel canister. The canisters have an in-room placement in a vault that, in the Kristallin-I safety assessment, is located in a low-permeability crystalline host rock block. A compacted bentonite clay buffer surrounds the canisters in the vault. The bentonite is assumed to have a homogeneous fine pore structure. The complete corrosion of the glass matrix in a canister is expected to take over 150,000 years. The groundwater in the spatially varying fractures and rock matrix has total dissolved solids that varies from 1 to 13 g/L.

In preference to crystalline rock, NAGRA (2002) proposed the Opalinus Clay of the Zurcher Weinland in Switzerland as a host rock for a HLRWM facility. The formation has a thickness of more than 100 m at a depth of 600 m to 750 m. The estimated hydraulic conductivity of the formation is 10^{-13} m/s parallel to the bedding plane and 2×10^{-13} m/s normal to the bedding. The principal reasons for the selection of the Opalinus Clay as a host rock are: the geologic environment is simple, the potential siting area is tectonically stable on the timescale of more than a million years, the mechanical properties of the formation ensure that repository-induced or natural discontinuities are self-sealed, the region has no resource potential, the geochemical environment has been stable for more than a million years, and the formation has good engineering properties. Combined, these features indicate excellent isolation potential for a HLRWM facility (NAGRA, 2002).

5. GEOSPHERE MODELS

As stated in the Seaborn Environmental Assessment Panel (1998) report: “Any predictions of environmental and human health effects over time periods of tens of thousands of years will be subject to debate, criticism and differences of opinion because it is not possible to validate them directly. Thus, computer models play an important role in judgments concerning the long-term safety of the (HLRWM) concept." There has been a significant improvement in data processing, model application, and data visualization since the work described in the EIS (Davison et al., 1994) study. New and sophisticated computer models have been developed for the description of the geosphere.

A computer simulation model is a mathematical representation of those physical and chemical characteristics of a particular site, and those processes acting at the site and its surroundings, that are believed to control the movement of contaminants from the disposal vault to the biosphere during the time of the quantitative assessment of risk. Identifying the important pathways for contaminant movement through the rock to the biosphere, and the factors that would be important in controlling contaminant movement along those pathways requires a thorough knowledge of the geologic, hydrogeologic, geomechanical and geochemical conditions of the site (Davison et al., 1994, pg 16). The three-dimensional finite-element code MOTIF was used to model aspects of the geosphere in both the EIS and the SCS (Davison et al., 1994; Stanchell et al., 1996). Other models that can be used to simulate the complex geosphere flow processes include SWIFT III and FRAC3DVS. The model FRAC3DVS has been developed since the EIS and SCS and this model, together with recently developed and implemented data management and visualization tools is yielding state-of-the-art site characterizations and safety assessments that support of studies of hypothetical and concept HLRWM facilities.

The MOTIF (Model Of Transport In Fractured/porous media) model is described in Chan et al. (1999). MOTIF 3.2 simulates three-dimensional saturated or unsaturated Darcian fluid flow, solute transport and heat transport with a dual porosity and discrete fracture formulation. The solute transport algorithm includes forced or natural convection, mechanical dispersion, molecular diffusion, equilibrium linear adsorption and single-species radioactive decay. The heat transport algorithm includes forced or natural convection, conduction and hydrodynamic dispersion. Fluid density is a function of pressure, temperature and concentration. Dirichlet, Neuman and Cauchy boundary conditions can be used for both solute transport and heat transport. The governing equations are solved numerically using the Galerkin finite element method. Temporal discretization is by a weighted first-order finite difference approximation. The Picard iterative scheme is used to solve the coupled non-linear flow and transport equations. MOTIF has been used extensively for the simulation of geosphere and vault processes.

The SWIFT model (Sandia Waste-Isolation Flow and Transport) was originally developed, maintained and applied by Sandia National Laboratories under the sponsorship of the U.S. Nuclear Regulator Commission. The three-dimensional model is based on the finite-difference method and is fully transient with steady-state options. It fully couples the equations for flow, heat and brine transport via fluid density, fluid viscosity and porosity. The model is applicable to saturated porous and fractured media with a dual porosity formulation being used for the latter. Verification and validation of the well-documented model is provided in Ward et al. (1984).

FRAC3DVS (Therrien et al., 2001) is a numerical algorithm or model for the solution of the three-dimensional variably-saturated groundwater flow and solute transport in discretely-fractured media. The model includes a dual porosity formulation while discrete fractures are idealized two-dimensional parallel plates. The numerical solution to the governing equations is based on implementations of both the finite-volume method and the Galerkin finite-element method. Versions of the model couple fluid flow with brine transport through the fluid density that is dependant on both pressure and brine concentration.

An important step in the development of a model that is part of the performance or safety assessment package is the development of the Requirements Specifications for the model. Requirements Specifications present the equations to be solved, the input and output requirements, and the structure of how the model is to be implemented. They quantify or define what should and will be in a model. The model is defined at sufficient depth that an experienced scientist in the appropriate discipline could quickly understand what was to be contained in the model. The Requirements Specifications would not, however, be so specific that they would outline the computer requirements (core, speed, peripherals, etc.), or the solution algorithms, or other similar details that would define precisely how a computer code would need to be developed. Rather, these later specifications have been termed Design Description.

The process through which the Requirements Specifications were defined generally consisted of the following steps:

1. Analyze the siting, design and licensing applications to identify the factors that influence the model requirements
2. Define the processes to be modeled including
   - The system, subsystem or components to be analyzed, e.g., the types of materials involved and their general size and shape.
   - The forces and processes that will act upon the system, subsystems or components
3. Define the general model requirements using the information from steps 1 and 2.
4. Develop the detailed model Requirements Specifications.

An important aspect of the development and use of Requirements Specifications is that the assumptions that limit what is to be considered under each application area must be defined. The Requirements Specifications for a model can be system dependent; for example, a geosphere model that may be appropriate for a vault system for the surface storage of used fuel may not adequately describe the geosphere for a vault with borehole emplacement of canisters.

6. CONCLUSIONS AND RECOMMENDATIONS

The Nuclear Waste Management Act, Bill C-27, specifies that three approaches must be considered for the management of high-level radioactive wastes. The three approaches are: deep Geological disposal in the Canadian Shield, storage at reactor sites and centralized storage either above or below ground. The importance of the geosphere and geospheric research is dependent on the approach being least important for above ground storage and most important for a below ground management system. Determining the importance of the geosphere is the degree to which it will be relied upon to minimize the impact on the biosphere of potential releases of radionuclides from a waste repository or vault. Current engineering, construction and hazardous waste handling practices are at a standard that ensures safe short-term surface and near surface HLRWM; however, the waste remains accessible and is not isolated from the human environment. Geosphere research and knowledge is well developed and there is a broad and diverse base of expertise for such systems. In comparison, research for deep geologic disposal of

HLRW is highly specialized and has been undertaken by a relatively small group of scientists and engineers. The EIS and SCS were largely the work product of AECL. An important outcome of the SRG (1995) and Seaborn Environmental Assessment Panel (1998) reviews of the EIS is that a wider base of expertise is being developed to undertake research on the deep geologic disposal of HLRW. This research base includes scientists and engineers in numerous consulting firms and universities as well as those at AECL, OPG and other power authorities.

In recent years, examples of important contributions to geospheric research relative to a deep disposal system include:

- improved methods for data management and visualization,
- the development of a new generation of site characterization and safety assessment models (FRAC3DVS is an example) that resolve the concerns in the SRG (1995) review. Models include the influence on fluid flow and radionuclide migration of increased pore water density in the deep rock. The paleoclimate evolution of the geosphere is being investigated using transient analyses.
- new methods for assessing the complex network of discrete fracture zones that are found in the Canadian Shield
- the study of the temperature regime and deep permafrost that occurs in northern sections of the crystalline rock of the Canadian Shield
- the determination of the hydraulic and transport properties of moderately fractured rock and discrete fractures
- the continued study of the hydrogeochemistry of crystalline rock
- a case study that involves rigorous world-leading site characterization and safety assessment of a hypothetical repository in the Canadian Shield.

The focus of much of this geospheric research has been and continues to be crystalline rock. Plutonic rock is widespread in the Canadian Shield; there are significantly fewer potential and accessible sites for a deep HLRWM facility in either shale or bedded salt.

Plutonic rock has been characterized in research at the WRA URL. The hydrogeochemical data indicate that below 500 m at the URL, groundwaters are very saline, reducing, and old. The groundwater can be considered as essentially stagnant over the period of concern for a HLRWM facility (10^6 years). The very low permeability of the rock supports this conclusion. From our understanding of the glaciation-deglaciation cycles that have occurred for the last 900,000 years, it is certain that the geosphere above a deep repository will be covered by ice before radionuclides in the repository can decay to insignificant levels. The impact of the thickness of the ice and remoteness of the biosphere are important factors that must be considered in safety assessment. The presence of the ice cover should reduce the impact of a repository on the biosphere.

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