CANADIAN GEOSCIENCE RESEARCH AND DEVELOPMENT IN SUPPORT OF ADAPTIVE PHASED MANAGEMENT: AN OVERVIEW

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Abstract

The Nuclear Waste Management Organization (NWMO) has the federal mandate to implement the Adaptive Phased Management (APM) approach for the long-term care of Canada's used nuclear fuel. The end point for APM is the safe emplacement of used nuclear fuel in a Deep Geologic Repository (DGR) situated in a stable crystalline or sedimentary bedrock formation. The DGR concept is comprised of multiple barriers designed to contain and isolate the used nuclear fuel on a timeframe of 1 Ma. A key element in the DGR design is the enclosing geosphere, which acts to protect the engineered barrier system(s), to preserve a stable environment in which radionuclide mobility is minimized, and to minimize the potential for intrusion. At a nominal depth of 500 m, the capacity of the geosphere to act as a natural barrier is governed by site-specific geologic features or attributes. As part of the APM Geoscience Technical Program, activities are undertaken to foster the development and optimization of multidisciplinary geoscience as they relate principally to surface based characterization of deep-seated (400-700 m) low permeability ($\leq 10^{-18}$ m^2), low porosity (≤ 0.1) and saline (TDS 50-300+ gm/L) settings. Such approaches are required to assess deep aquitard/aquiclude system evolution and dominant mass transport processes on timeframes relevant to a DGR safety case. This paper provides an overview of the NWMO APM Geoscience Technical Program and activities since 2011.

1. Introduction

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM), the Government of Canada selected approach for the long-term management of Canada's used nuclear fuel waste. The APM approach envisions that Canada's used nuclear fuel will be emplaced in a multi-barrier Deep Geologic Repository (DGR) at a nominal depth of 500 m to safely contain and isolate the waste form on time frames of 1 Ma. The geologic environs being considered by APM include Paleozoic age carbonate and shales, and portions of the crystalline Canadian Shield, in Ontario. In the case of either a sedimentary or crystalline rock setting preferred attributes include, among others, low permeability, low porosity and sufficient mechanical strength. The characterization of such geologic environs in order to support a DGR safety case presents unique challenges.

The site characterization process is iterative in nature and based, in part, on an approach involving multiple-lines-of-evidence. In this approach, an understanding of the site is developed through coordinated multi-disciplinary geoscience studies that, among others, include geology, structural geology, physical hydrogeology, hydrogeochemistry, isotope hydrology, seismicity, paleohydrogeology, glaciation and geomechanics. Key goals of these studies are to assess the natural attributes of the site at a scale commensurate with a DGR (i.e. footprint area ≈6 km^2), and to gain knowledge of the sites' past evolution. Of particular importance are the deep-seated low permeability formations, as they reveal information on both natural formation barrier properties and longevity, as well as groundwater system stability. The studies are not only broad in nature but also are conducted at a variety of scales: rock core in the laboratory (nm-cm), in-situ testing in cored boreholes (cm – dm), and local to regional watershed (≈100 to 1000 km). The studies also involve collaborative applied research and demonstration experiments within Underground Research Laboratories (URL). Combined, these multi-disciplinary activities can be synthesized to provide a reasoned conceptual understanding of the geosphere in terms of its stability, resilience and predictability, all of which provide confidence in assessing site suitability and the ability to establish a strong repository safety case.

This paper presents an overview of the NWMO APM Geoscience Technical Program, including specific activities and international collaborative studies. In part, the Geoscience Technical Program takes into account experience from Canadian and international repository siting programs associated with the iterative development of a Geosynthesis. A Geosynthesis represents an understanding of the past, present and future evolution of a proposed repository site based on multiple lines of reasoning. The Geoscience program is comprised of more than 25 specific studies. Activities are sub-divided into two key areas: i) geoscientific site characterization; and ii) synthesis and numerical analysis. The entire program is described in the 2015 NWMO APM Annual Technical report [1]. A brief summary of the geoscience program supported by examples of current work is provided in the following sections.

2. Geoscientific Site Characterization Activities

2.1 Porewater Characterization

Perhaps one of the single most important factors in site characterization is the reliable characterization of porewaters contained within the accessible pore space of the rock matrix. An understanding of the distribution of porewater compositions within deep-seated groundwater systems can provide insight on the history of past fluid movement and dominant mass transport mechanisms at time and space scales not otherwise achievable [2,3,4]. While not excluding efforts to ensure sample preservation during drilling and coring operations, significant challenges remain in the extraction of representative porewaters from retrieved rock cores with low porosities (0.003 – 0.08), low water content (<7%), low permeability ($<10^{-18}$ m^2), high ionic strength (1-7 M), secondary mineral fluid inclusions, and free and structurally bound water. For crystalline rock, the methods applied are well developed, established, in part, through the Scandinavian radioactive waste management work programs [5]. For sedimentary rock, a wider range of methodologies exist, including new techniques involving isotopic equilibration, cellulose paper, porewater squeezing (>100MPa) [6], micro-vacuum distillation, and crush and leach at various rock:water ratios.

Key activities in porewater characterization are being undertaken at both the University of Ottawa and the University of Bern. As part of the work at Ottawa, a novel technique that passively absorbs porewater onto cellulose paper has been developed, with the pioneering efforts originally conducted at the University of New Brunswick [7]. Improvements in reliability and precision are being sought through modification of the methodology to minimize the influence of evaporation on the cellulose paper prior to analysis. At the University of Bern, sequential high pressure mechanical squeezing of indurated and highly over-consolidated clay rich (<25%) sediments, between pressures of 100 and 500 MPa, is yielding encouraging results for elemental and isotope chemistries, based on comparison to alternative means [6]. While pressure dependent mineral dissolution, anion exclusion effects and ion filtration occurring under collapsing pore structure represent potential sources of error, the ability to use squeezing techniques as a means to reliably characterize the distribution of a broad range of environmental tracers that preserve evidence of past solute migration is judged as high.

Stable water isotope (^{18}O, ^{2}H) distributions within low permeability, deep-seated groundwater systems can offer insight into system stability and resilience to glacial perturbations occurring within timeframes of interest to repository safety. Complications in porewater extraction resulting from varied clay mineralogy, typically low water contents and highly saline fluids provide key challenges in obtaining reliable results. Micro Vacuum Distillation (µVDE) and Adaptive Isotope Diffusive Exchange (AIDE) provide two complementary methods for ^{2}H and ^{18}O porewater determination [8]. Dependent on clay mineralogy, the two methods may yield varied isotopic compositions that are attributed to: i) bound and diffusive double layer water in clay minerals, and/or ii) structurally bound water within secondary evaporate minerals, being released and altering the composition of the mobile water fraction within the interconnected porosity. Current research activities are focused on refining methodologies to understand the relative roles of bound and structurally bound waters on the determination of porewater compositions.

2.2 Rock Matrix – effective diffusion coefficients

Within low permeability groundwater systems, solute mobility can be significantly influenced by diffusion. Exploring the role of diffusion requires the completion of a range of complementary studies including petrophysics, the estimation of effective diffusion coefficients (D_e) for the rock matrix, and transferrable analogues at formation scales that allow inverse modelling of conservative environmental tracer (Br, Cl, ^{18}O, ^{2}H) distributions to yield estimates of up-scaled mass transport properties and governing mechanisms. Combined, these studies can yield site-specific estimates of diffusion properties for various lithologies and provide direct evidence supporting their application in numerical simulations of mass transport at the scale of a groundwater system enclosing a repository. The determination of matrix diffusion properties can be complicated given low permeabilities, complex pore geometries and interconnectivity (as influenced by pore fluid compositions (porewater and gas)), high porewater ionic strengths, secondary mineral precipitation, anisotropy, and ionic charge. The development of methods for site-specific application have been an important area of research in the Geoscience program.

Applied research is conducted in three areas: i) laboratory estimation of effective diffusion coefficients for saturated and partially saturated media; ii) assessment of the diffusive double layer in clay-rich sediments and its influence on anion diffusion and estimates of porewater compositions; and iii) natural analogue studies that enable constrained interpretation of governing solute migration processes at time frames beyond those required to demonstrate repository safety.

With respect to methods development, laboratory based studies focused on estimation of D_e are undertaken at the University of Ottawa. These studies are advancing the application of innovative 2-

and 3-dimensional computed tomography (CT) techniques originally developed at the University of New Brunswick [9, 10, 11]. Recent advances include the acquisition of a higher-power x-ray CT system at the University of Ottawa Advanced Research Complex (ARC), that through further minimizing signal to noise ratios and a greater dynamic range in x-ray detection, enables improved resolution of tracer migration for more accurate estimates of matrix porosity and D_e. Based on current knowledge, the research has focused on examining uncertainties in D_e estimates and demonstrating the application of refined techniques to study diffusion. The main areas of study include: i) the influence of rock core relaxation and decompression on laboratory estimates of D_e; ii) the role of preferential diffusive pathways along mineral grain boundaries, microfractures, argillaceous and dolomitized mineralization on D_e estimates; iii) the influence of free gas phase (partial saturation) on estimates of D_e (Figure 1); iv) estimation of effective pore diffusion coefficient for ^{137}Cs and ^{90}Sr; and v) determination of apparent diffusion coefficients for CH_4, CO_2 and He.

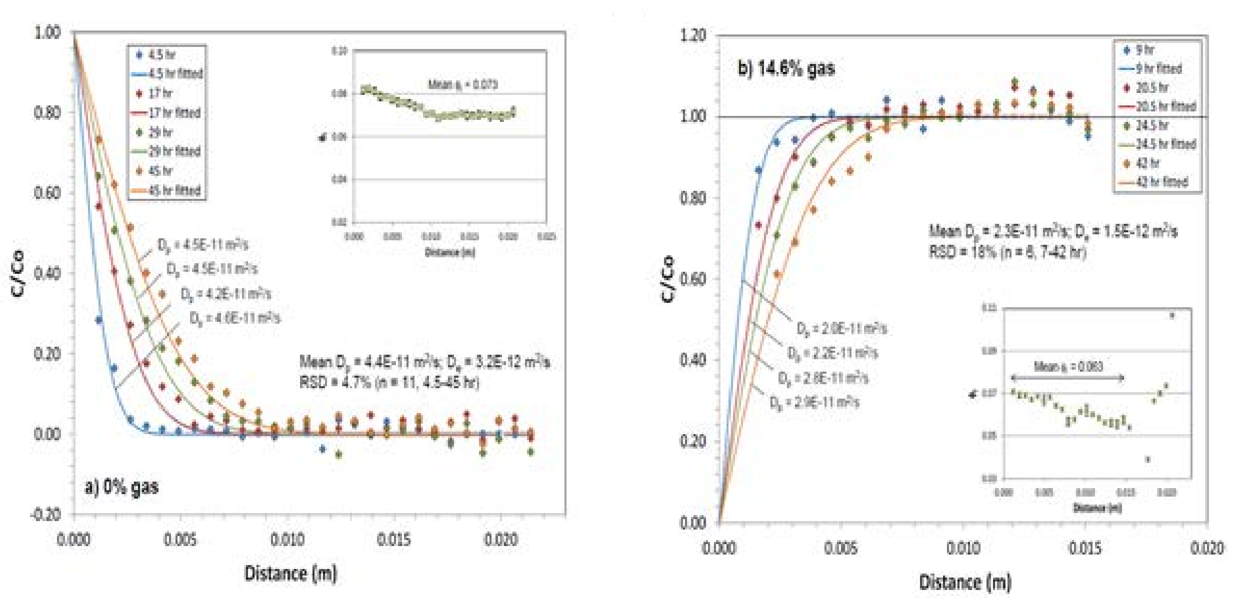

Figure 1. Tracer diffusion data for a) fully brine-saturated and b) partially brine-saturated Queenston Formation (shale) sample.

In the Canadian context a unique aspect in understanding diffusion is associated with the high ionic strength (5-7M) of the porewaters occurring in crystalline and, in particular, sedimentary rocks. For neutral and positively charged chemical species, the whole pore space of a clay-rich sedimentary rock is available for transport, however, anions are repulsed by the negatively charged clay mineral surface. Hence, only a part of the pore space is available for anion transport (i.e., the anion porosity is less than the total porosity), and this anion accessible porosity increases with increasing ionic strength. This could be explained by a better shielding of the negative surface charges at higher ionic strength, resulting in less repulsion of the anions from the surface. In this regard, the ANPOR project is a jointly funded research program with the Paul Scherrer Institute (PSI; Switzerland) that is investigating anion exclusion effects in clay rocks on Canadian (Queenston and Blue Mountain formations) and Swiss (Opalinus Clay and Helvetic Marl) samples. The interim results of this study demonstrate a clear relationship between the ionic strength of the porewater and the anion accessible porosity.

2.3 Geomechanics: long-term rock strength degradation

A time-dependent rock behaviour testing program was initiated in 2014 to investigate the static fatigue (constant stress) and relaxation (constant axial strain) behaviour of the Swiss Jura and Canadian Cobourg limestones. Empirical evidence from underground excavations [12], numerical back-analysis [13] and laboratory testing [14] suggests that the lower bound rock strength limit or long-term strength of rock could be represented by the rock crack initiation (CI) stress. This phenomenon was observed during static fatigue testing of the Lac du Bonnet granite from Pinawa, Manitoba, for which a strength threshold was observed at a driving stress ratio of about 0.45. This value coincides with the CI of the rock at about 45% of Unconfined Compressive Strength (UCS).

The current testing program at ETH Zurich aims to provide further evidence that the CI is a lower bound strength using 76 mm diameter rock core from the Jura and Cobourg limestone formations. Testing began on the Jura limestone to ensure the testing procedure and sensors would yield reliable data prior to testing of the Cobourg limestone. The time to failure for the Jura limestone matched very closely with results obtained for the aforementioned Lac du Bonnet granite (Figure 2). The static fatigue test results for the Cobourg also indicate a similar trend. The static fatigue testing program for the Cobourg limestone will be completed in 2016. This testing program is providing evidence that the CI stress threshold provides a reasoned estimate that bounds long-term rock strength.

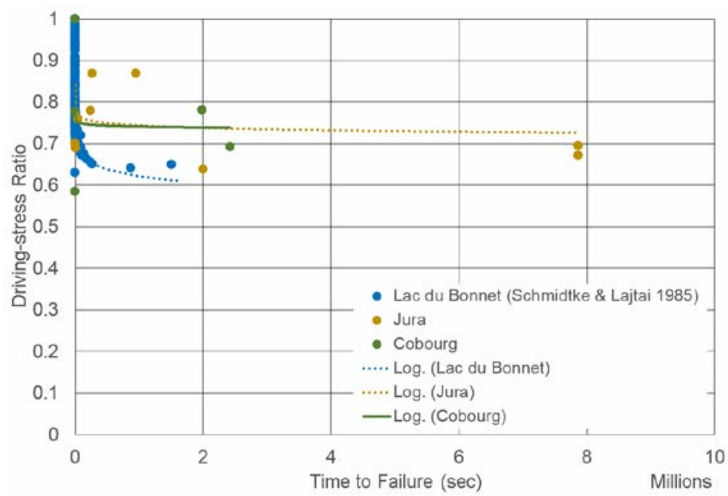

Figure 2: Preliminary static fatigue test results for the Jura and Cobourg limestones.

2.4 Fracture Mineral Infill – paragenesis

In assessing geologic suitability, a key aspect relates to natural barrier formation longevity associated with fracture formation and fluid movement. Mineral-filled fractures and openings (e.g., veins and vugs) in a rock mass provide evidence that fluid migration events have occurred at some point in the geologic past. Vein and vug emplacement may be related to diagenesis (in sedimentary rocks), orogenic activity and/or past geologic uplift, and erosion. Characterization of secondary fracture mineral infills includes determination of absolute age, mineral assemblages, layering (cathodeluminence), and fluid inclusion homogenization temperatures and composition. The results can provide evidence related to fracture age, episodic fluid movement within the fracture, and the composition of fracture fluids at the time of mineral precipitation as related to prevailing geologic conditions.

As part of the broader study of fracture characterization, a program involving radiometric Uranium-Lead (U-Pb) age analysis of vein calcite is ongoing at the University of Toronto's Jack Slattery Geochronology Laboratory [15,16]. Complimentary work is being undertaken by the Rock and Water Interaction (RWI) group at the University of Bern with respect to fluid inclusion analysis [17]. Thus far, the research has focused on proof of concept application using fracture calcites within a Cambrian to Devonian age sedimentary sequence on the eastern flank of the Michigan Basin.

2.5 Canadian Shield - regional ground stress database

An important element in repository design relates to the nature and magnitude of in-situ rock stresses. In-situ stresses are rarely uniform, as their distribution depends on a number of factors such as rock mass characteristics (i.e., heterogeneities, fabric, discontinuities, geological structure, etc.) and the site loading history (e.g., tectonic activity, erosion and/or glaciation). As part of this work program a review and compilation of reported rock stress measurements within the Canadian Shield was performed. This effort represented an update of an earlier 2005 stress database comprised of 229 reported stress measurements. The post-2005 data base comprised 304 measurements with depths ranging between 12 to 2,552 m. Acceptance criteria were used to screen the data to select estimates of increased quality. The resulting screened database, which comprised 199 measurement results (173 - 2005; 26 - post-2005), was then used to establish depth-dependent stress domains and develop illustrative equations with which to predict stress magnitude in these domains [18].

2.6 Seismicity - paleoseismicity

Given the timeframe in which a DGR must function, external perturbations such as those associated with rare strong earthquake ground motions require consideration. As part of site characterization activities, Probabilistic Seismic Hazard Assessments would be performed that generate a seismic source model consisting of large regional source zones that are used to simulate the occurrence of distributed earthquake activity. Seismic source characterization provides a model for the rate of occurrence, spatial distribution and size distribution of earthquakes surrounding the site. The primary data used in justifying this probabilistic model are from the earthquake catalogue. Current activities in this regard focus on: i) maintaining the Canadian Hazards Information Service (CHIS) network of seismographs to monitor seismic activity in Northern Ontario and eastern Manitoba [19]; and ii) paleoseismic investigations of regional watershed soft sediment lakebed deformation [20].

In the paleoseimic studies, the mapping and identification of submarine landslides within lake-bottom sediments at the regional watershed scale are used to improve knowledge of seismic hazard. To this end, the Geologic Survey of Canada has selected a watershed region on the Canadian Shield near the Rouyn-Noranda, in northwestern Quebec, to explore and demonstrate this methodology. The work has involved two steps: i) the mapping of landslide deposits using a sub-bottom acoustic profiling system that produces 2-dimensional geophysical images of the sub-bottom; and ii) the collection of the lake-bottom sediment cores from the frozen lake surface. These latter core samples are used to date the landslide events primarily by analyzing the thickness pattern of varved sediments that either overlie or are interbedded with the landslide deposits. To date, the research has revealed multiple landslide events primarily occurring within glaciolacustrine sediments indicating a Holocene age, possibly 8,000 BP, at the time of last glacial retreat and presence of post-glacial Lake Ojibway. These multi-landslide signatures are good candidates for evidence of ancient earthquakes, although conclusions are pending and need to be supported by evidence from other lakes within the watershed.

2.7 Fracture Network Interpretation

In crystalline rocks, the presence and distribution of fracture zones in the geosphere strongly influences groundwater system dynamics and evolution. The predominant pathway for groundwater flow and solute migration is through the interconnected network of transmissive fractures. To aid in the synthesis of field data and the derivation of discrete fracture network models closely representing field information, a geostatistical approach [21, 22] is being advanced in collaboration with MIRARCO, the Centre for Excellence in Mining Innovation (CEMI) and Laurentian University. The applied research is focused on the development and application of the code MoFrac that is intent on rendering 3-dimensional realizations of fracture networks at multiple length scales. Key features of the code include: i) geospatial referencing of observed structural discontinuities; ii) the ability to capture fracture hierarchy and truncation for various fracture sets; iii) probabilistic fracture network realizations that can be explicitly linked to groundwater system uncertainty analyses; and iv) the ability to incorporate 3-dimensional field data from surface and sub-surface investigations. A particular focus at the moment is code validation, which is being achieved through blind comparison tests with mapped fracture networks of a recent excavation at the crystalline Äspö Hard Rock Laboratory in Sweden. An example of a comparison between a predicted MoFrac realization and actual mapped fracture traces at the Äspö HRL is shown in Figure 4. A description of MoFrac and the validation exercise is documented [23].

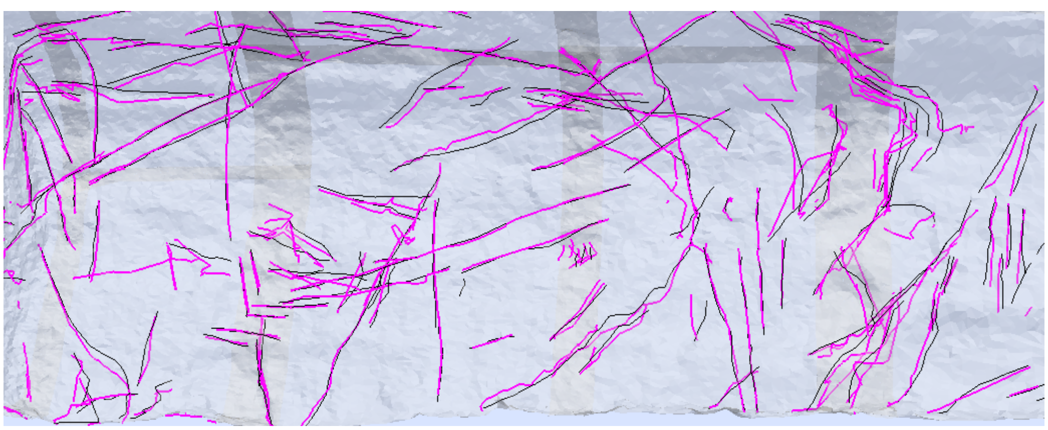

Figure 4 – Comparison of Äspö field mapped and MoFrac generated fracture traces.

3. Case Studies - synthesis and numerical analysis

3.1 Sedimentary Basin Groundwater System Evolution - reactive transport modelling

As part of the APM program, developing an understanding of groundwater system evolution is particularly important as it relates directly to the repository safety case in providing evidence of system stability on geologic time and space scales. Numerous processes may influence and interact to affect groundwater system stability, including site-specific hydrostratigraphy, variable density fluids, heat and mass transport, water–rock interactions, and mechanical loading by ice-sheets. To explore these phenomena and their interaction, development of a reactive mass transport code, MIN3PTHCm, has been undertaken in collaboration with the University of British Columbia. Documentation of recent advances in code development, parallelisation, verification and application in benchmark experiments and case studies is available [24, 25, 26].

A particular application of MIN3PTHCm involved an illustrative case study to assess the hydrodynamic and hydrogeochemical impacts of glaciation on a type intra-cratonic sedimentary basin [27]. The simulations, performed over a time frame of 32,500 years to capture a single ice-sheet advance and retreat, were conducted in 2-dimensions for an approximate 400 km wide sedimentary basin comprised of interbedded sandstones, shales, evaporates, and carbonates in the presence of dense brines. The results reveal that although high hydraulic gradients may be imposed on the groundwater system by glacial meltwater and mechanical loading, the low permeability of the underlying sediments maintains stable conditions within deep-seated portions of the basin. The brines reduce the impact of geochemical reactions on groundwater chemistry and exert a strong influence on the depth of penetration by basal glacial meltwater, the surface hydraulic head of which can exceed present day conditions by ≈2 km for a temperate glacier during glacial maximum. Although processes such as de-dolomitization and halite precipitation are predicted to occur in the near surface, the effect on porosity and deep groundwater system evolution is not material.

3.2 Crystalline Groundwater System Evolution - paleohydrogeology

Glaciation due to long-term climate change will be the strongest external perturbation on the geosphere and groundwater system at potential repository depths. The advance and retreat of glacial ice, and the corresponding mechanical and hydraulic loading and unloading, can potentially influence the groundwater system behaviour at depth [28]. Numerical groundwater modelling provides a means to analyze the impact of future glacial events on a given groundwater system. In the event of glaciation in a fractured crystalline rock geosphere, the interconnected network of fractures will act as potential conduits, allowing glacially derived meltwater to recharge into the system to depth. Dense brines at depth can lessen energy gradients and act as a barrier to the recharge and depth of penetration of low salinity, oxygenated glacial meltwater that could influence radionuclide mobility.

The effect of surface boundary conditions during glacial advances and retreats on groundwater systems was investigated using numerical groundwater models to help illustrate the long-term evolution and stability of a crystalline rock geosphere to external perturbations. These analyses were done through the use of multiple glacial boundary condition time-series datasets. The glacial boundary conditions include ice-sheet history over the past 120,000 years, and include scenarios representing cold and warm based ice-sheets, as well as an updated boundary condition dataset representing the current best estimate [29, 30]. The glacial boundary condition dataset includes times-series data on ice-sheet thickness and permafrost depth. The glacial boundary conditions were represented in the numerical model using 1-dimensional vertically constrained hydromechanical coupling, where the boundary conditions specified both the mechanical load as a result of the ice-sheet advance and retreat, as well as a corresponding increase in hydraulic head at surface. Depth of surficial recharge (as a proxy for meltwater recharge) was used to illustrate the influence of glaciation on the groundwater systems (Figure 4). The depth to which surficial recharge will penetrate is strongly influenced by the hydraulic conductivity and interconnectedness of the fracture network. The influence of the glacial boundary conditions and hydromechanical coupling was illustrated through use of sensitivity cases, where the increase in hydraulic head as a result of the ice-sheet buildup was varied.

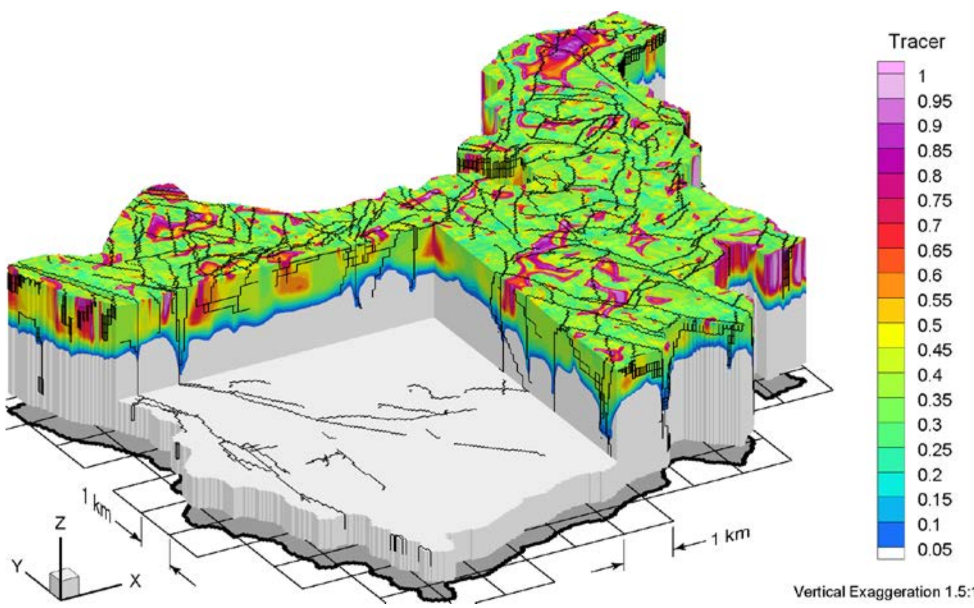

Figure 4: Paleohydrogeologic simulation of glacial meltwater (tracer) recharge within a fractured crystalline groundwater system following a 120ka glacial cycle [28]
(Note: Elevation at base of domain -1250 masl; depth of domain nominally 1600 m).

3.3 Self Analogues – case studies

As discussed, self or site analogues provide a means to characterize groundwater system properties and behaviour at time and space scales not otherwise achievable. In specific cases, such analogues relate to distinct hydrogeochemical, isotopic and/or hydraulic signatures preserved within deep-seated low permeability groundwater systems. Within the APM program, integrated activities have been undertaken to illustrate the application of similar analogues in Canadian sedimentary settings, including analysis of the vertical distribution of ^{18}O and Cl^- through a near horizontally bedded 400 m thick sequence of Ordovician shale and carbonates [4]. Numerical simulation, in consideration of reasoned boundary conditions, strongly supports the existence of an ancient diffusion-dominant transport regime in which fluid and solute migration has been unaffected by natural perturbations, including recent Pleistocene glacial episodes, at geologic timescales beyond 100 Ma.

Another analogue case study involved the analyses of strong (250+ m) formation hydraulic underpressures in the same sedimentary sequence and yielded estimated formation scale vertical hydraulic conductivities of 10^{-14} m/s or less [31]. An international assessment of the significance of hydraulic underpressures is published [32]. These types of integrated studies provide alternative arguments for confidence in system properties and notions of long-term stability that contribute to a repository safety case.

4. Conclusions

The NWMO Adaptive Phased Management (APM) Geoscience Technical Program is oriented toward advancing and preserving science related to the study of deep-seated (400-700 m), saline (1-7M), low permeability ($\leq 10^{-18}$ m^2) and low porosity (≤ 0.1) groundwater systems in crystalline and sedimentary settings. Key aspects of the program focus on method development to explore the long-term stability and resilience of groundwater systems, and the integrity of natural barriers enclosing a used nuclear fuel Deep Geologic Repository (DGR). Specific studies relate directly to site characterization activities in refining and validating methods to reliably define system properties. They also include work related to further establish the understanding of radionuclide and contaminant mobility under electrochemically reducing conditions, and to test that understanding through site-specific analogues with geochemical, isotopic and hydraulic signatures that preserve evidence of past natural barrier longevity. Collaborative studies with international radioactive waste management organizations and involvement in demonstration experiments at Underground Research Laboratories (Mont Terri (Switzerland); Äspö (Sweden)) provide additional means to test and jointly assess issues relevant to repository safety on timeframes of geologic significance (i.e., 1 Ma). Canadian advances in these areas of geoscience are positioning the APM program to improve site characterization capabilities and increase confidence in a DGR safety case.

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