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THE DEEP GEOLOGIC REPOSITORY TECHNOLOGY PROGRAM: DEVELOPING A GEOSCIENTIFIC BASIS FOR REPOSITORY SAFETY

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ABSTRACT

The Deep Geologic Repository Technology Program (DGRTP) has been managed and directed by Ontario Power Generation (OPG) since the late 1990's. A key aspect of the DGRTP has been to coordinate geoscience studies that advance Canadian geoscience expertise and methodologies for the characterization and simulation of regional and sub-regional Shield environs at timeframes relevant to demonstrating the safety of a Deep Geologic Repository (DGR) for used nuclear fuel. Within this context the DGRTP Geoscience program is intent on integrating multi-disciplinary geoscientific studies to reveal common lines of reasoning that are fundamental to communicate the role and capacity of a crystalline Shield setting to assure long-term waste isolation. This requires development of a basis to convey our understanding of the processes and mechanisms, and site-specific geologic attributes that affect or govern flow domain hydrodynamic and geochemical stability at time scales of 100,000 years and beyond. This paper provides an overview of DGRTP Geoscience research activities and, in particular, how they are contributing to a geoscientific basis for understanding and communicating aspects of DGR safety.

1. INTRODUCTION

The Deep Geologic Repository Technology Program (DGRTP) is advancing the geoscientific basis for understanding the safety of the Deep Geologic Repository concept for long-term nuclear used fuel management. In this role, the DGRTP is fostering the development of geoscience methods and tools capable of generating an improved understanding of deep-seated Shield groundwater flow system evolution at time scales extending to 100,000 years and beyond. In part, this is being achieved through the development of illustrative case studies in which evidence is assembled to demonstrate concepts of flow system evolution and create a basis for a broader dialogue and consensus on geoscience and climate change issues that materially affect confidence in the predicted long-term performance of the DGR concept.

The Geoscience work program is conducted through the coordinated efforts of 20 groups drawn from 10 Canadian universities, consultants, federal government organizations and international research institutions. Specific areas of investigation include Shield geology, structural geology, remote sensing, geostatistics, hydrogeochemistry, isotope hydrogeology, hydrogeology, paleohydrogeology, natural analogues, numerical methods, seismicity, long-term climate change (i.e. glaciation) and scientific visualization. The work program has been established to, among other issues, examine approaches for the integration and linkage of geoscientific reasoning that attempt to constrain inherent non-uniqueness and uncertainty associated with the interpretation and prediction of Shield flow system dynamics and evolution at time scales relevant to DGR implementation. Through this approach an improved fundamental understanding of Shield flow system evolution and applicability of techniques to communicate this understanding are being developed.

Determining the suitability of a specific site will require an assessment of geosphere stability. Stability has broad meaning that includes both repository engineering considerations, and the geosphere processes and mechanisms that govern subsurface groundwater flow and mass transport. With respect to geosphere processes, one aspect of stability is the resilience or constancy of the groundwater flow system (i.e. groundwater flow paths; groundwater residence times/ages; poised reducing electrochemical conditions) to foreseeable change in flow system property distributions, boundary conditions or both. An example would be that of glaciation, which during the latter half of the Pleistocene markedly altered the landscape of the Shield through cyclic periods of temperate, boreal, peri-glacial, then ice-sheet cover and retreat on an approximate 100,000 year timeframe.

The response or behaviour of the geosphere with respect to long-term change is determined by factors such as site-specific fracture or discontinuity frequency, orientation, geometry and interconnectivity, variable groundwater salinity, watershed topography and permeability distributions within rock mass volumes that exceed several km^3. Unique transient boundary conditions and site characteristics will govern to a certain extent the migration of environmental isotopes, hydrogeochemical flow system signatures, fracture infill mineral assemblages, as well as groundwater flow pathways and the depth of penetration by oxygenated glacial recharge - all related points that either through consistency in interpretation or occurrence contribute to knowledge regarding geosphere barrier integrity and long-term stability. Developing tools with improved utility to explore and communicate how such foreseeable long-term events and site-specific geologic features affect confidence in the prediction of long-term geosphere barrier performance is a key goal in the DGRTP.

In Section 2 of this paper, the status of the used nuclear fuel disposal program in Canada is reviewed, and background information relevant to the overall DGRTP is provided. An overview of the DGRTP Geoscience work program goals and specific work program activities are provided in Section 3. In Section 4, the main elements of the Geoscience work program are discussed, with an emphasis on projects and new methodologies that are advancing the geoscientific basis and reasoning for understanding Shield groundwater evolution as relevant to the siting and safe implementation of the DGR concept. A summary is provided in Section 5.

2. BACKGROUND

In November 2002, the Canadian Government brought into force the Nuclear Fuel Waste (NFW) Act. The NFW Act addresses the long-term management of used nuclear fuel in Canada by defining a process and timetable for the selection of a preferred management option. The NFW Act also required the creation of a Nuclear Waste Management Organization (NWMO), the formation of which was announced in October 2002. The NWMO is directed to undertake a study of approaches for the management of used fuel, including, but not limited to, storage at nuclear reactor sites, centralized storage either above- or below-ground and deep geologic disposal on the Canadian Shield. This study, which will involve broad public consultation, will compare the benefits, risks, and costs of each approach. The NWMO must submit its study and accompanying recommendation for a preferred approach to the federal government within 3 years of the NFW Act coming into force (November 2005). The government will then select an approach for implementation by the NWMO. The earliest decision by the government is expected in 2006.

On behalf of the nuclear fuel waste owners in Canada, Ontario Power Generation's (OPG's) DGRTP conducts research and development activities associated with advancing the DGR concept. A key issue within the program remains the geosynthesis of site-specific information, which provides a traceable and reasoned basis to constrain predictive outcomes through analysis and integration of multi-disciplinary data, despite recognized site characterization uncertainties. Synthesis of broadly diverse but corroborating geoscientific evidence can improve the traceability of geologic reasoning that bounds non-uniqueness and offers a systematic approach to communicate and convey confidence in the expected long-term performance of the geosphere (Jensen and Goodwin, 1999; 2003). This approach responds to technical remarks made during the Seaborn Panel hearings on the Environmental Impact Statement and Second Case Study (AECL, 1994; Goodwin et al. 1996). A brief description of the DGRTP Geoscience work program approach and specific work program activities is provided in the following section.

3. GEOSCIENCE WORK PROGRAM

The philosophy adopted in developing the Geoscience work program includes the following considerations:

i) Descriptive Conceptual Geosphere Model:

An emphasis is placed on co-ordination of work programs to improve clarity and transparency of the geoscientific evidence and logic that supports the development of an integrated, site-specific, multi-disciplinary, descriptive, conceptual geosphere model. This process serves several roles within the DGRTP including: a) a systematic framework to assemble and test flow system hypotheses; b) a forum in which multi-disciplinary groups are engaged to understand how their data influences confidence in the descriptive and predictive model outcomes; c) a basis to constructively convey a sense of data worth to investigators who might not otherwise appreciate the utility of their information; and d) a method to demonstrate to site characterization groups improvements in methods of data collection, interpretation or both that best serve to instill confidence in predictive estimates of DGR performance.

ii) Deep Seated Flow Domain:

The Geoscience program aims at developing tools and multiple lines-of-reasoning for advancing the understanding of physical and chemical stability of deep flow systems (500-1000 m) in fractured-porous media at time scales of 100,000 years. This includes the development of tools and methods applicable in either crystalline or sedimentary rock settings.

*iii)	Non-Uniqueness:*

In geoscience, non-uniqueness is problematic. Current work program activities and new initiatives are directed toward addressing issues of spatial and temporal uncertainty such that the robustness in predictions can be best demonstrated. Further, this approach is developed recognizing practical limitations during DGR investigations on the ability of site characterization techniques and methods to allow complete or unique characterization of required rock mass volumes.

*iv)	Multiple Lines of Reasoning:*

Based on non-uniqueness, a process is required to ensure that multi-disciplinary evidence is used to constrain both the conceptual descriptive geosphere model(s) and predictive numerical realizations for flow or mass transport. In this regard, it is important to demonstrate how reasoning independent of modelling (i.e. paleohydrogeology; isotopic flow domain systematics, hydrogeochemistry; natural analogue investigations) can enhance confidence in predictive outcomes.

*v)	Peer Review:*

Independent technical peer review is an important aspect of the Geoscience work program. Peer review serves two primary roles: a) it provides for open communication with the geoscientific community to solicit candid feedback; and b) it maintains and fosters technical credibility in the DGRPT Geoscience program.

DGRTP Geoscience Work Program Activities

Within the overall Geoscience program there are 4 theme areas addressing both fundamental and applied geoscience research: a) Site characterization methodology development; b) Geosynthesis; c) Groundwater flow and mass transport in crystalline rock masses; and d) Regional - Sub-regional scale Shield flow system evolution as affected by long-term climate change. A brief description of current or recently completed DGRTP Geoscience work programs is summarized in Table 1. A more complete description of these work program activities can be found in OPG (2004).

Table 1: Summary of Current or Recently Completed DGRTP Geoscience Work Program Activities

	Geoscience Work Program	Program Description
1	Long-Term Climate Change: Numerical Realization of Laurentide Glacial Cycle	Application of the University of Toronto Glacial Systems Model to derive geophysically constrained realizations of the last Laurentide glacial cycle (121 kyr BP - present). This model provides a geoscientific basis to understand ice-sheet dynamics, ground surface temperature, isostatic depression, and permafrost evolution as would occur at a representative Shield location (Peltier 2002; 2003; 2004).
2	Analogue Studies: PERMAFROST Case Study	A joint international research project investigating the influence of permafrost on groundwater flow system evolution during the Quaternary in a continuous permafrost crystalline rock setting to depths of 1100-m (i.e. Lupin Mine Nunavut) (Frape et al, 2004; Geologic Survey of Finland, 2004)
3	Hydrogeochemistry: WRA Hydrogeochemical Case Study	A compendium and synthesis of hydrogeochemical data gathered within the Whiteshell Research Area (Lac du Bonnet batholith) relevant to developing an understanding of site-specific groundwater flow system evolution and dynamics during the Quaternary and beyond. (Gascoyne 2000; 2004)
4	Hydrogeochemistry: Pore Matrix Fluid Experiment	A series of controlled laboratory experiments with saturated rock core designed to demonstrate a methodology to derive representative pore matrix fluid elemental and isotopic compositions in extremely low permeability crystalline rock.
5	Paleohydrogeology: WRA Fracture Mineral Infill Case Study	A paleohydrogeologic study of fracture infill mineralogy and isotopic composition within the Lac du Bonnet batholith as relevant to the evolution of fracture fluid compositions and the depth of penetration by low-salinity oxygenated glacial recharge. (McMurry and Ejeckam, 2002; Gascoyne et al 2003; 2004)
6	Regional/Sub-regional Shield Groundwater Flow System Analysis	A reasoned, 3-dimensional, numerical analysis (FRAC3DVS) of groundwater flow within a regional (5700 km^2) and sub-regional (100 km^2) watershed that is assessing 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. (Normani et al., 2003; Sykes et al. 2002; 2003; 2004; Srivastava 2002b)
7	WRA Lineament Analysis Case Study	An interpretative and systematic GIS based lineament analysis of the WRA using historic and remotely sensed data sets. This study is continuing to explore the application of laser altimetry (LiDAR) to aid in surface based site characterisation and lineament interpretation. (Sikorski et al, 2002; 2003; Srivastava 2002a)
8	Fracture Network Modelling	A geostatistical methodology for the development of field constrained and geologically reasoned 3-dimensional Fracture Network Model(s). (Srivastava 2002a; 2003; 2004)
9	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. (McMurry, 2000)

Table 1 (concluded):

	Geoscience Work Program	Program Description
10	Numerical Methods: Reactive Transport Modelling - Redox Stability	A reactive transport insight modelling study in which the role of coupled physical, chemical and biological processes governing the evolution of redox state within a Shield flow domain are being examined. (MacQuarrie and Mayer, 2003)
11	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).
12	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 and pore water diffusion coefficients. Joint international activities conducted at the Äspö Hard Rock Laboratory Long-term Diffusion experiment. (Vilks et al., 2003; 2004)
13	Quarried Block Experiment	A series of flow and tracer (solute/colloid) experiments and accompanying numerical simulation within a single (variable aperture) 1 m^2 fracture plane (Brush, 2003).
14	Site Characterization: Hydraulic Well Test Analysis – nSIGHTS	An application of numerical methods for uncertainty analysis related to the interpretation of transient flow and pressure well bore tests to derive estimates of transmissivity and storativity in intact and moderately fractured granitic rock. (Roberts, 2003; 2004)
15	Site Characterization: Canadian Shield Seismic Activity Monitoring	A continuation of low-level seismic activity monitoring in Northern Ontario with a 20 station seismograph network. (Drysdale et al., 2004)
16	Site Characterization: Apatite Fission Track Thermochronology	An international collaborative study of Apatite Fission Track Thermochronology as relevant to Canadian Shield tectonics, thermochronology and fracture generation/history. (Everitt et al. 2002)
17	Geosynthesis: Scientific Visualization	The application of scientific visualization technologies, including a Virtual Reality Laboratory 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. (Cotesta and Kaiser, 2002; 2004; Cotesta et al., 2004)
18	Numerical Methods: DECOVALEX THMC	An international forum in which coupled Thermal-Hydraulic-Mechanical codes are being applied to investigate flow system stability as affected by glaciation. (Chan and Stanchell, 2004)
19	International: NEA AMIGO	The NEA 'Approaches and Methods for Integrating Geologic Information in the Safety Case' (AMIGO) is an international forum for the exchange of information and discussion on the collection and integration of geologic information in repository siting, design, safety assessment and the repository Safety Case. (Jensen and Goodwin, 2003; NEA, 2003)

4. SHIELD GROUNDWATER FLOW SYSTEM EVOLUTION: A BASIS FOR UNDERSTANDING

As previously discussed, one specific goal of the Geoscience program is associated with assembling geoscientific evidence to advance the understanding of groundwater flow system evolution and dynamics during the Quaternary within deep-seated regional (≈5000 km^2) and local scale (≈100 km^2) Shield settings. This involves a multi-disciplinary approach that is intent on providing a structured and systematic framework to reveal: i) the relative importance of site-specific flow domain property attributes and geometry, and boundary conditions on flow domain stability; ii) the impact of site characterization uncertainty with respect to realization of property distributions and boundary conditions; and iii) geoscientific indicators of stability that foster reasons for confidence or otherwise in the repository Safety Case.

In order to constrain the understanding of flow system evolution, the approach adopted involves developing multiple-lines-of-reasoning with respect to processes and mechanisms contributing to an understanding of long-term flow system stability. In so doing, work program activities have been purposely linked or aligned such that collectively they create a means to communicate aspects of Shield flow system evolution. Figure 1 provides a diagram illustrating the linkage in work program areas that focus on issues of groundwater flow system stability, recognition of which is a central tenet in communicating the potential suitability of a host site (e.g. repository is within a diffusion dominated regime, despite expected flow system perturbations, at timeframes relevant to repository safety).

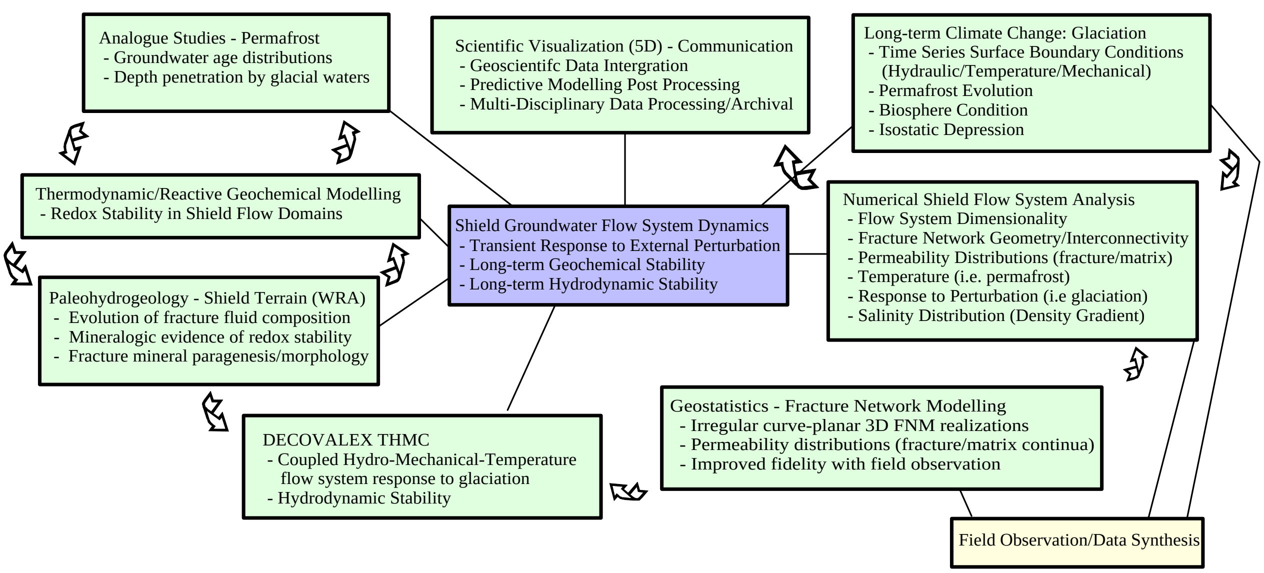

Figure 1: Multiple-Lines-of-Reasoning and Linkage of DGRTP Geoscience Programs to Develop a Geoscientific Basis for Repository Safety.

In part, this approach provides for a means to constrain uncertainty and non-uniqueness in geoscientific understanding, as well as a systematic and structured framework within which to explain the derivation and assembly of a site-specific descriptive conceptual geosphere model. Further explanation of the work program and contributions to the DGRTP are provided in the following sections.

4.1 Regional and Sub-regional Shield Flow System Simulations

The program activities during 2004 focused on numerical simulations at the local or sub-regional flow system scale (Sykes et al., 2004). The model applied was a hybrid, discrete-fracture, dual continuum realization of the finite element model FRAC3DVS. The modelling approach included use of a realistic Digital Elevation Model (DEM) of the flow domain's topography, the explicit discretization of a 3-dimensional, curve-planar, Fracture Network Model (FNM) that honoured many site-specific geological, statistical, and geomechanical constraints (Srivastava, 2002) , and the use of fine discretization grids that improved upon the previous studies of a similar nature. The regional and inset sub-regional flow domains, the Fracture Network Model and a realization within the FRAC3DVS grid are shown in Figure 2.

As part of the analysis, a single realization of the complex FNM was superimposed onto a 600,000 element FRAC3DVS flow domain mesh. Orthogonal fracture faces (between adjacent finite element blocks) were used to approximate the irregular FNM comprised of more than 540 individual discontinuities. The crystalline rock mass between these structural discontinuities was assigned a range of properties considered characteristic of Shield terrain. Simulation results that reveal and capture the complex distribution of Darcy fluxes within one realization of the flow domain are shown in Figure 3. In all of the simulations performed, predicted Darcy fluxes at depths below approximately 600 m are indicative of mass transport regimes in which diffusion would be the dominant transport mechanism. Future work program activities will be devoted to coupling sub-regional flow system simulations with transient long-term climate change surface boundary conditions, uncertainty analysis to incorporate multiple and equally probable FNM realizations, groundwater salinity and spatially-correlated permeability fields in both fracture and matrix continua. The intent is to advance the utility of FRAC3DVS to enable a more rigorous and complete assessment of flow domain uncertainty as it affects the potential siting and development of a Safety Case for a DGR within a crystalline or sedimentary rock environ.

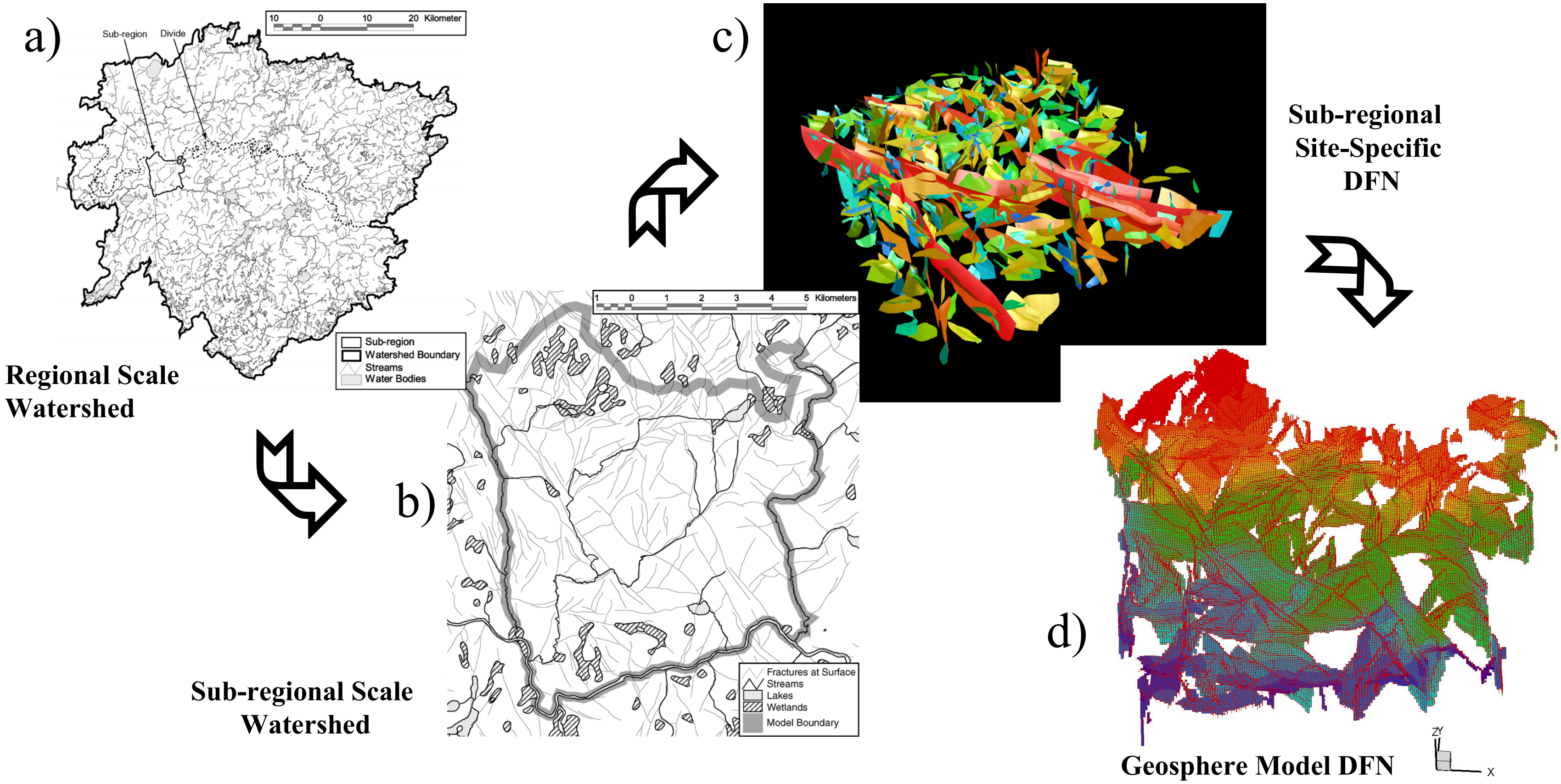

Figure 2: Integrated process through which regional and sub-regional scale models are combined with geostatistical (3D) discrete fracture network (DFN) realizations for flow and transport simulations; a) regional flow model domain; b) sub-regional flow model domain; c) geostatistical realization of FNM model at sub-regional scale; and d) realization of FNM model in sub-regional FRAC3DVS grid.

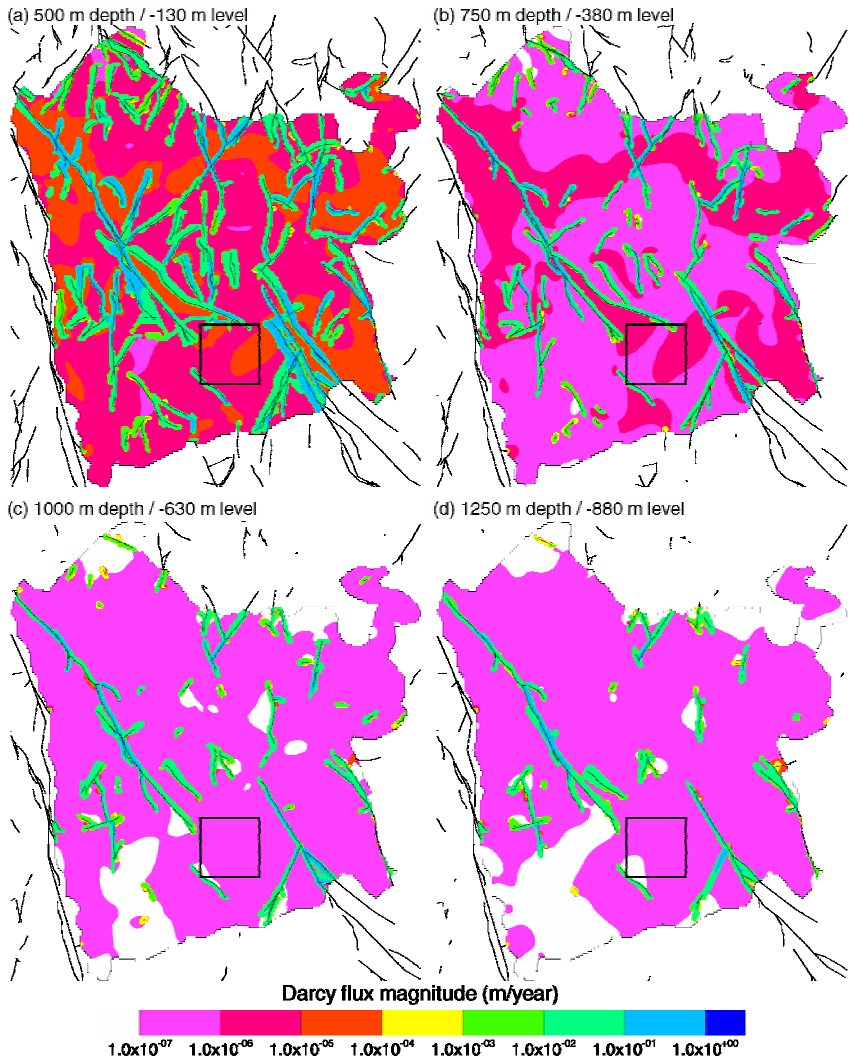

Figure 3: Predicted distribution of groundwater Darcy fluxes at selected depths within a representative sub-regional Canadian Shield flow domain, based on 3-dimensional, steady-state, freshwater, numerical simulations with FRAC3DVS (Sykes et al., 2004)

Further activities related to improving the utility of predictive tools have involved the implementation of Time Travel Probability techniques within FRAC3DVS. This technique involves the solution of the advection-dispersion equation to derive Probability Density Functions (PDFs) that represent the statistical occurrence of water particles with respect to time as a consequence of mixing processes. Such PDF's can be representative of groundwater age (time since recharge) or life expectancy (time to discharge). Notable is that the technique can preserve site-specific flow system dimensionality, fracture network geometry , permeability distributions and contrasts, salinity distributions and time varying boundary conditions. An example that illustrates predicted mean life-expectancy for a single realization within the aforementioned sub-regional flow domain is shown in Figure 4. This innovative technique is beginning to provide a further basis to understand and provide reasoned visualization of the magnitude of uncertainty in computed age determinations as affected by flow system properties and boundary condition uncertainty. In so doing it is yielding a constructive means to explore and illustrate coincidence with other site characterization field data sets, for example hydrogeochemical or environmental isotope distributions, with the intent of fostering confidence in knowledge of bounds on flow system behaviour.

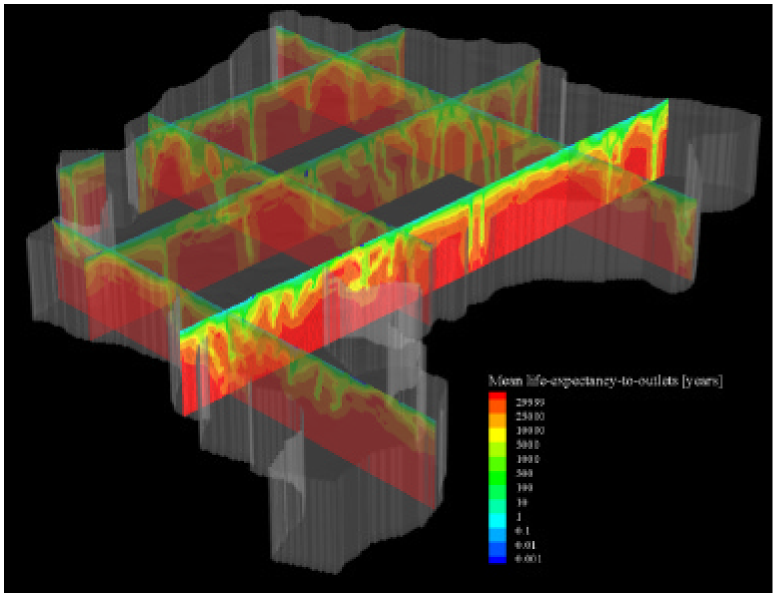

Figure 4: Mean Life Expectancy (time to discharge) for the sub-regional flow domain based on implementation of the Travel Time Probability technique within FRAC3DVS. Results are based on a single, steady-state, fresh-water realization of the sub-regional flow domain as described in Sykes et al. (2004)

4.2 Long-term Climate Change - Glaciation and Permafrost

Within the northern latitudes of Canada, the performance of a Deep Geologic Repository (DGR) for used nuclear fuel at depths of 500 to 1000 m within the crystalline rock of the Canadian Shield will be affected by long-term climate change. As surface conditions are predicted to change from present day boreal to peri-glacial, variable ice-sheet thickness cover and then rapid glacial retreat (8-10 kyr), coincident transient geochemical, hydraulic, mechanical and temperature conditions will be imposed on the Shield flow system.
With respect to understanding Shield groundwater flow system dynamics and stability, an important consideration is the influence of the gradual or episodic nature of such transient boundary conditions on, for example, the magnitude and rate of change in groundwater flow rates/directions, the depth of penetration and mixing of surface-fracture-matrix end member waters, depth of redox front migration and changes in rock stress magnitude and orientation.

Work program efforts related to furthering the understanding of long-term climate change and glaciation have focused on advancing climate-driven, predictive estimates of the last continental glaciation with the University of Toronto Glacial Systems Model (GSM). These simulations yield geophysically constrained estimates of Laurentide ice-sheet geometry, advance and retreat, ground surface temperatures, basal ice-sheet meltwater fluxes, glacial isostatic depression and, more recently, permafrost evolution. An example of the complex and dynamic nature of surface and permafrost conditions reasonably expected to influence a hypothetical Shield site is shown in Figure

5. Figure 5 depicts one realization of the GSM that predicts ground surface temperatures, ice-sheet normal stress (equating to ice-sheet thickness) and coincident ground temperature changes to depths of 3 km. Although preliminary in nature, these latter estimates yield plausible approximations of freezing depths as constrained by an understanding of the current occurrence of permafrost and coincidence with time-series ground surface temperature data derived through inversion of deep borehole temperature logs from 4 Shield locations. A more detailed description of the GSM model and the methodology applied for predictions of ground temperatures and permafrost evolution are provided by Peltier (2003) and Peltier (2004), respectively.

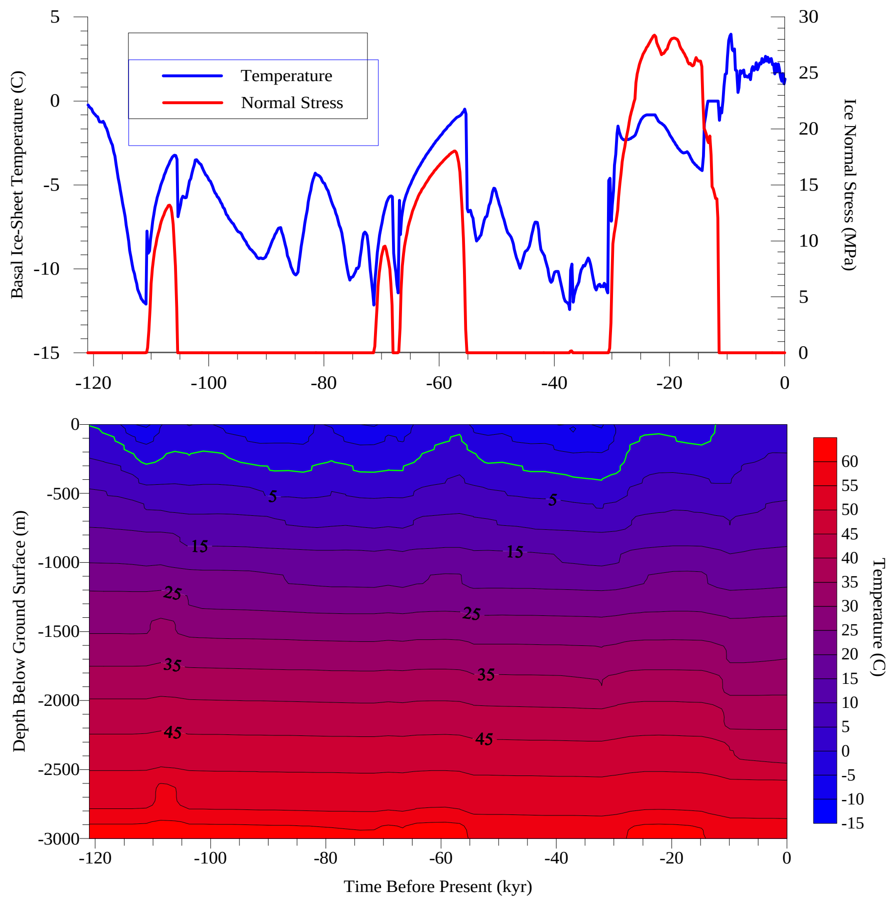

Figure 5: University of Toronto Glacial Systems Model - prediction of Laurentide ice-sheet and permafrost evolution at a representative Canadian Shield site: a) time-series estimates of ground-surface temperatures and normal stress (ice-sheet thickness); and b) time-series estimates of ground temperatures depicting depth of freezing point (permafrost) during glacial cycle

4.3 DECOVALEX THMC

The international DECOVALEX-THMC project (acronym for International co-operative project for the DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation) was initiated in 2004, and will last for three years. The DGRTP is participating in

DECOVALEX THMC Task E, which has the goal of deriving a complementary geoscientific basis for communicating implications of coupled mechanical-hydraulic-thermal processes and mechanisms arising from long-term climate change and glaciation on groundwater flow system dynamics. The case definition for Task E considers the sub-regional flow domain realization described in section 4.1 and boundary conditions consistent with those derived through GSM simulations as described in section 4.2. Specific aspects of geosphere evolution during a glacial event that will be explored as part of Task E activities include:

- Shield flow system property distributions and geometric attributes governing depth of penetration by surface recharge to a DGR during a glacial event;
- The influence of variable salinity distributions on groundwater flow system stability or transient disequilibrium during a glacial event;
- The influence of fracture orientation and interconnectivity on transient groundwater flow rates/paths and fracture rejuvenation/displacement; and
- Aspects of hydrogeochemical flow system evolution during glacial cycles that may corroborate field observation and yield alternative reasoning to support the existence of a long-term diffusion-dominated repository flow domain.

Through focusing on issues of geoscientific relevance to Shield flow system evolution and response to external perturbation, Task E will provide an integrated Case Study and a more quantitative basis to illustrate the significance of site-specific flow system property distributions and geometry on time dependent integrity and stability of the geosphere barrier.

4.4 Paleohydrogeology - WRA Mineral Infilling Case Study

The evolution of redox conditions at the repository horizon which can influence long-term engineered barrier system performance and sub-surface radionuclide mobility remains an important issue for predicting long-term DGR performance. In addressing this issue, paleohydrogeologic studies within the variably fractured Lac du Bonnet batholith at the Whiteshell Research area have been undertaken to examine secondary fracture mineral infill paragenesis, isotopic composition and mode of occurrence to assess indicators of past depths of recharge by low salinity oxygenated glacial recharge (McMurry and Ejeckam, 2002; Gascoyne et al. 2004). Evidence suggests that no substantive indicators for low-temperature mineral reactions with oxidizing waters were found below a depth of 20 metres. Further and on-going work in this regard is exploring evidence of redox front migration that may be better preserved as altered iron valence ratios in less reactive silicate minerals, or as aluminosilicate weathering products that are more resistant to reductive dissolution. This work involves the application of state-of-the-art analytical transmission electron microscopy (ATEM) techniques for the determination of past changes in the redox state of iron in fracture minerals. These ATEM techniques provide a new suite of tools to investigate chemical and mineralogical changes at the nanometre scale; the scale at which weathering processes related to oxygen diffusion along mineral grain boundaries occurs. Work program activities are continuing to develop and demonstrate a possible paleohydrogeologic methodology with an expectation that such approaches could be effectively applied to demonstrate an understanding of redox front migration and stability at repository depths during the geologic past.

4.5 Reactive Transport Modelling

Another approach to assessing the redox stability of a flow system is to simulate the long-term evolution of hydrogeochemical conditions in fractured crystalline rock using predictive numerical models. In particular, reactive transport models offer the possibility of investigating scenarios that depend on coupling physical, chemical and biological processes of direct relevance to redox conditions in groundwater systems. In 2004, a work program was initiated based on the state-of-science review conducted by MacQuarrie and Mayer (2003), which identified model requirements and potential applications of such models within the DGR Technology Program. The main objectives of the work program are: a) to provide a greater understanding of basic processes controlling redox stability under assumed vertical transport of oxygenated recharge water in fractured crystalline rock; b) to perform a comprehensive uncertainty analysis of processes affecting redox stability from surface to repository depths of 500 to 1000 m; and c) to evaluate the applicability of two conceptually different model formulations (Discrete Fracture and Dual Continuum) to simulate reactive transport in deep and variably fractured rock systems.

The work program involves reactive transport modelling that progresses from small-scale mechanistic simulations to larger-scale geochemical stability investigations in several stages. In the first stage, a base case scenario for recharge of oxygenated waters in a single fracture system was developed, guided in part by existing DGRTP hydrogeochemical, paleohydrogeological and mineralogical data. Transient transport boundary conditions were considered to account for the change in oxygen and carbon dioxide partial pressure and organic carbon content in the recharge solution; parameters that could change significantly during periods of glaciation and deglaciation. Preliminary simulations with and without dissolved inorganic carbon conducted over a period of 10 000 years suggest that oxygen ingress into the fracture and the width of the alteration rim adjacent to the fracture are both strongly dependent on the assumed partial pressure of oxygen in the recharge water, and on the initial mineralogy.

4.6 Natural Analogue - Permafrost

PERMAFROST is an international project involving OPG, Nirex, Posiva, SKB and the Geological Survey of Finland. The purpose of this project is to further advance the scientific understanding of permafrost and its role in influencing flow system evolution and fluid movement in crystalline terrain. Field research is conducted at the Lupin Mine in Nunavut, Canada, which is situated approximately 1300 km north of Edmonton in an area where continuous permafrost extends to a depth of over 500 m.

Work program activities have involved a stepwise approach intent on developing a conceptual descriptive model of the mine site that would complement the interpretation of groundwater geochemistry and isotopic systematics. Related mine site investigative activities to date have involved electromagnetic geophysical surveys to define the lateral variation of permafrost and saline groundwater depths, drilling research boreholes at the base of the permafrost, rehabilitation of boreholes at depth within the mine for hydrogeochemical sampling and hydraulic testing, sampling of surface waters, and hydraulic pressure measurements. The most recent work program activities have involved hydraulic testing to define the lateral extent of the observed unsaturated zone, dating of the deep groundwaters and synthesizing the hydrogeochemical data collected at depths to 600 m beneath the permafrost. Interim results are providing evidence of a heterogeneous deep-seated flow system in which groundwater ages are pre-Quaternary or much older. Through undertaking such analogue projects, evidence for flow system stability, particularly if coincident with regional and sub-regional flow system simulations, is yielding another line of reasoning that may be useful in explaining assertions of long-term flow system stability.

4.7 Scientific Visualization

A DGRTP work program was initiated at MIRARCO, based at Laurentian University, to explore the utility and application of Scientific Visualization supporting the integration, validation, visualization and communication of complex numerical modelling results associated with the development of the conceptual geosphere model for the next generation sub-regional (100 km^2) Shield flow system (Sykes et al., 2004) and the evolution of this flow system as affected by long-term climate change. New advanced visualization techniques are being developed to facilitate the querying, interpretation and integration of: i) multiple, geostatistically-simulated, fracture network model (FNM) realizations that form the basis for the geosphere model used as input to FRAC3DVS; ii) geostatistically-generated permeability fields associated with the fracture networks and the rock domains between the fractures to depths of 1000 m; iii) the FRAC3DVS model grids, as well as the results of transient simulations of groundwater flow evolution (Darcy fluxes, pressure head changes, groundwater residence times, salinity changes etc.) as a function of alternative FNMs and spatially variable permeability fields; iv) the influence of coupled climate/surface boundary conditions associated with a Laurentide glaciation scenario on the abovementioned simulations; and v) the linkages to multi-disciplinary data sets (ex: hydrogeochemical and isotopic data) that help to constraint/support the above modelling results.

Ultimately, the main goal of this work program is to develop an approach to data integration and communication that facilitates the understanding of the role and importance of flow system characteristics and evolution pathways that control mass transport in sub-regional scale Shield environments. This goal will be facilitated within a collaborative immersive virtual reality environment, where ideally “the data should speak for themselves”.

Progress in 2004 included the development and application of plug-ins for the Gocad™ earth modelling software for the purpose of importing various data sets such as the multiple realizations of the FNM model (up to 100), the FRAC3DVS model including nodes, rock mass elements, fracture elements and associated properties, and the result of a steady state flow simulation including hydraulic heads and Darcy velocities. Figure 6 illustrates an example of data integration where Realization 1 of the FNM model is painted with steady-state Darcy fluxes from the corresponding FRAC3DVS model grid. Note that the extent of the FNM model is larger than the FRAC3DVS model boundaries.

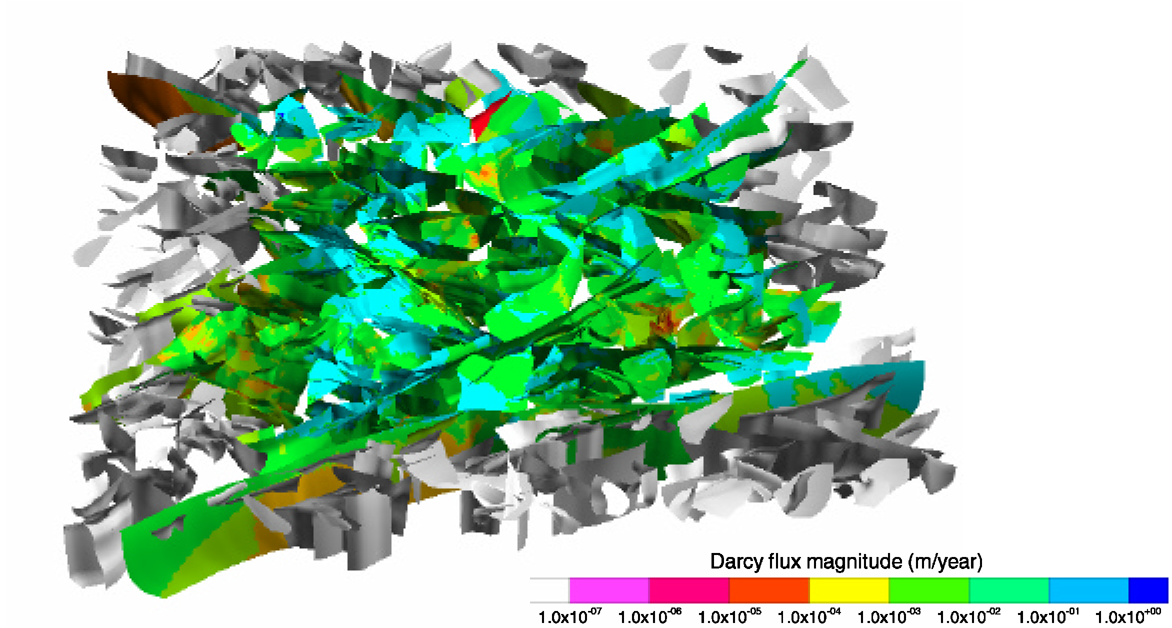

Figure 6: Integration of one realization of the FNM model with steady state Darcy flux output from corresponding FRAC3DVS model grid

5. SUMMARY

Within the Deep Geologic Repository Technology Program (DGRTP) several Geoscience activities are focused on advancing the understanding of groundwater flow system evolution and geochemical stability in a Canadian Shield setting as affected by long-term climate change. A key aspect is developing confidence in predictions of groundwater flow patterns and residence times as they relate to the safety of a deep geologic repository for used nuclear fuel waste. This is being achieved through a coordinated multi-disciplinary approach intent on: i) demonstrating coincidence between independent geoscientific data; ii) improving the traceability of geoscientific data and its interpretation within a conceptual descriptive model(s); iii) improving upon methods to assess and demonstrate robustness in flow domain prediction(s) given inherent flow domain uncertainties (i.e. spatial chemical/physical property distributions, boundary conditions) in time and space; and iv) improving awareness amongst geoscientists as to the utility of various geoscientific data in supporting a safety case for a deep geologic repository.

This multi-disciplinary DGRTP approach is yielding an improved understanding of groundwater flow system evolution and stability in Canadian Shield settings that is further contributing to the geoscientific basis for understanding and communicating aspects of DGR safety.

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