GLACIATION AND GEOSPHERE EVOLUTION – GREENLAND ANALOGUE PROJECT

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ABSTRACT

The deep geological repository concept for the long-term management of used nuclear fuel involves the containment and isolation of used nuclear fuel in a suitable geological formation. A key objective of the Canadian Nuclear Waste Management Organization (NWMO) geoscience technical research program is to advance the understanding of geosphere stability and its resilience to perturbations over time frames of relevance to a deep geological repository.

Glaciation has been identified as the most probable and intense perturbation relevant to a deep geological repository associated with long-term climate change in northern latitudes. Given that the North American continent has been re-glaciated nine times over the past million years, it is strongly expected that a deep geological repository within a suitable crystalline or sedimentary rock formation in Canada will be subject to glaciation events associated with long-term climate change. As such, NWMO's geoscience research program has placed particular emphasis on investigations of the response of the geosphere to glaciations. As surface conditions change from present day conditions to periglacial, followed by ice-sheet cover of variable thickness and rapid glacial retreat, transient geochemical, hydraulic, mechanical and temperature conditions will be simultaneously imposed on groundwater systems. NWMO research activities related to glaciation events and their impacts on groundwater system evolution are being undertaken using a multi-disciplinary approach aimed at collecting multiple lines of evidence. These investigations include assessment of the:

- Impact of an ice sheet on groundwater composition at repository depth using the Greenland Ice Sheet as an analogue to future glaciations in North America;
- Expected physical and temporal surface boundary conditions related to potential future glaciation events by estimating the magnitude and time rate of change of ice sheet thickness, ground surface temperature and permafrost occurrence, amongst other attributes;
- Evolution of deep groundwater systems and impacts of Coupled Thermo-Hydro-Mechanical effects imposed by glacial cycles;
- Impacts of climate change on redox stability using both numerical simulations and paleohydrogeological investigations; and
- Potential for seismicity and faulting induced by glacial rebound.

This paper presents an overview of studies underway as part of the Greenland Analogue Project (GAP) to evaluate the impact of an ice sheet on groundwater chemistry at repository depth using the Greenland Ice Sheet as an analogue to future glaciations in North America. The study of the Greenland Ice Sheet will allow us to increase our understanding of hydrological, hydrogeological and geochemical processes during glacial conditions.

1. INTRODUCTION

To advance the understanding of processes associated with glaciation and their impact on the long-term performance of a deep geological repository, the Greenland Analogue Project, a four-year (2009-2012) field and modeling study of the Greenland Ice Sheet and subsurface conditions, was undertaken collaboratively by the Canadian, Swedish and Finnish nuclear waste management organizations (NWMO, SKB and POSIVA, respectively).

The Greenland ice sheet is considered to be an analogue of the conditions that are expected to prevail in Canada and Fennoscandinavia during future glacial cycles. The overall objective of the Greenland Analogue Project (GAP) is to improve current understanding of how an ice sheet affects groundwater flow and water chemistry at repository depth. GAP aims to further investigate the:

1) Sources of subglacial waters;
2) Depth of glacial meltwater penetration;
3) Chemical composition of water at repository depth (~500 m);
4) Pressure gradients at the bed of an ice sheet;
5) Role of taliks (unfrozen ground in regions of permafrost) in front of an ice sheet; and
6) Impact of permafrost on the groundwater system.

The study will therefore allow us to increase our understanding of hydrological, hydrogeological and geochemical processes during glacial conditions.

1.1 GAP STUDY AREA

The Greenland Analogue Project study area is on the Western side of Greenland, near the town of Kangerlussuaq (Figure 1). The study area is in a region of continuous permafrost, and encompasses a land terminus portion of the Greenland Ice Sheet east of Kangerlussuaq (eg. [1]).

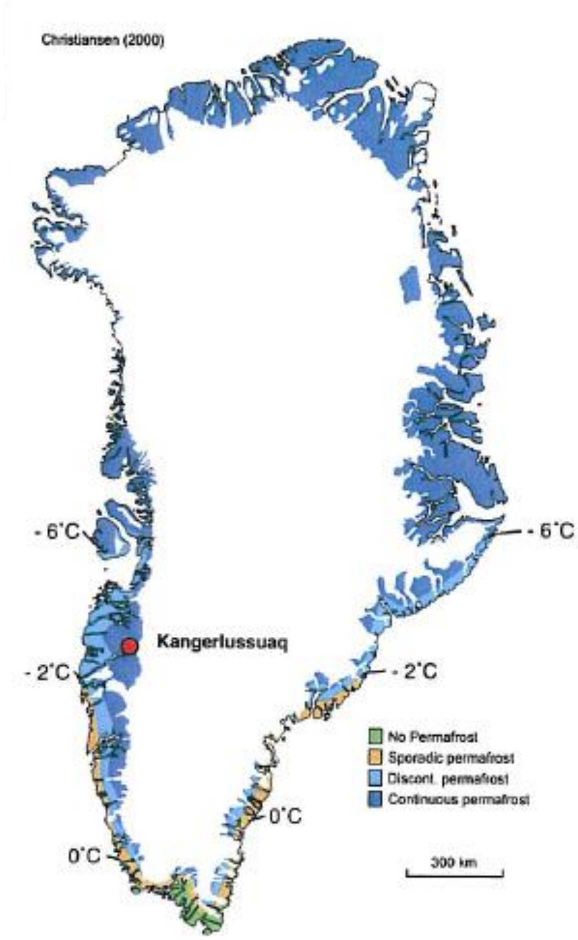

Figure 1. Location of Greenland Analogue Project study area (near Kangerlussuaq, Greenland) [2].

1.2 OVERVIEW OF THE GAP SUB-PROJECTS

The Greenland Analogue Project includes three sub-projects (SPA, SPB and SPC), each with specific individual objectives, but which collectively contribute data and process understanding to the overall GAP objective (Figure 2).

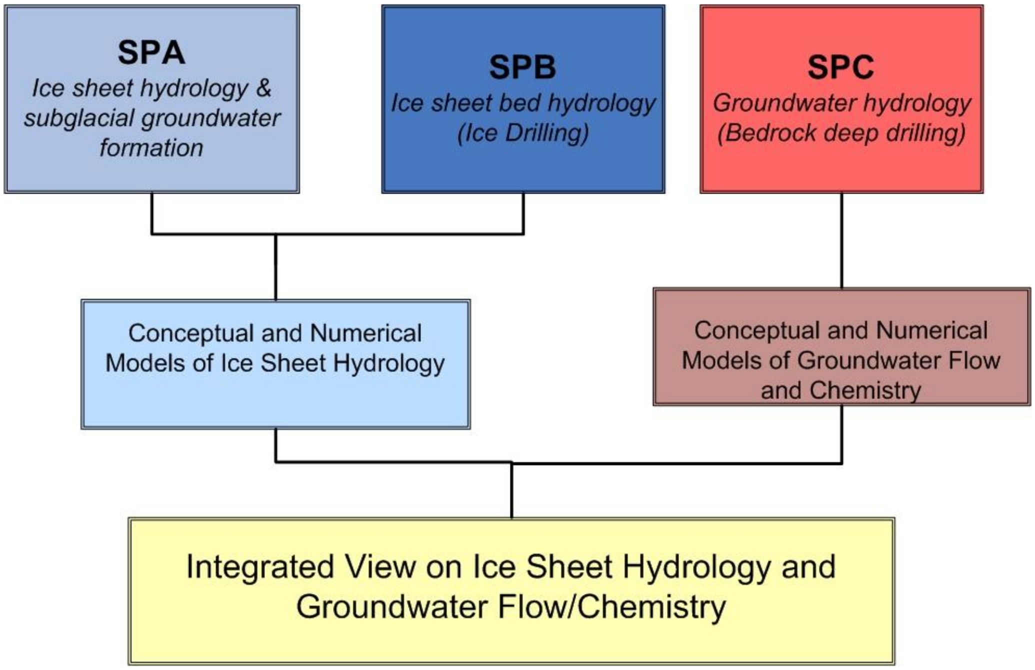

Figure 2. Illustration of how information from the GAP sub-projects feed into conceptual and numerical models, resulting in an integrated understanding of hydrological, hydrogeological and geochemical processes during glacial conditions.

Sub-project A: Ice sheet hydrology and sub-glacial groundwater formation

The main focus of sub-project A (SPA) is to improve the understanding of ice sheet hydrology in order to assess how an ice sheet impacts groundwater circulation and composition at repository depth (~500 m below ground surface). Data collected as part of SPA will be utilised in numerical ice sheet flow and hydrological modelling. SPA focuses on indirect observations of the properties of the hydrological system at the base of the ice sheet and on identifying which parts of the ice sheet contribute water that potentially infiltrates into the geosphere acting as a groundwater source. The latter includes quantifying melt-water production on the ice sheet surface and understanding how the water is routed from the surface through to the base of the ice sheet. SPA research activities include measuring ice velocity variations and surface melt water production. Major field activities as part of SPA include the installation and monitoring of GPS receivers and automatic weather stations on the ice sheet, as well as conducting both airborne and ground-based radar studies.

Sub-project B: Sub-glacial ice sheet hydrology

The main focus of SPB, as in SPA, is to improve the overall understanding of ice sheet hydrology. SPB focuses on direct observations and measurements of the characteristics of the hydrological system at the base of the ice sheet. The data collected in SPB will be used as inputs/boundary conditions in numerical ice sheet flow and hydrological models. One of the major field activities for SPB is using a hot water drill to drill through the ice sheet down to ice/bedrock interface. Boreholes are being drilled in many locations on the ice within the study area, particularly in areas where SPA radar surveys have indicated that the ice sheet is wet-based in order to observe water pressures at the interface between the ice and bedrock. In addition to the ice drilling, collection of remote sensing data of surface conditions will be carried out. SPB is providing pioneering measurements of sub-glacial water pressures beneath an ice sheet, giving important input to the conceptualization of hydraulic gradients during glacial conditions.

Sub-project C: Bedrock drilling, hydrogeochemistry and hydrogeology

SPC is studying the penetration of glacial melt water into the bedrock, groundwater flow and the chemical composition of water when and if it reaches repository depth (around 500 m depth). Main activities for SPC involve drilling boreholes through the bedrock in front of the ice sheet for subsequent down hole surveys and hydrogeological/hydrogeochemical instrumentation, sampling and monitoring. The deep drilling requires a detailed understanding of the geology of the area, including fracture frequencies and composition of rock types and hydrogeochemical information (i.e. chemistry of different water end-members). Boreholes to investigate the existence of talik beneath a lake, and to evaluate the depth of permafrost near the ice margin have been completed, and a deep, inclined borehole at the margin of the ice sheet down to ~500 m depth is planned for summer 2011.

1.3 SUMMARY OF GAP SUB-PROJECT ACTIVITIES

Sub-project A Activities

SPA has carried out several field campaigns to-date. These campaigns focused on: 1) deployment and maintenance of automatic weather stations (AWS) and GPS stations; 2) testing of the deep-look radar equipment; and 3) investigating the hydrological processes and feedbacks and testing of passive seismic equipment. An extensive archive of real-time satellite remote sensing datasets was obtained to better constrain the surface elevation and dynamics of basal hydrological mechanisms. From this archive it has been possible to obtain Russell Glacier Catchment-wide (i.e., GAP study area) constraints on annual, seasonal and specific temporal snapshots of surface speed, initial lake and moulin distribution, drainage and network connections along with the temporal-development and drainage characteristics of supraglacial lakes.

The GAP project and SPA has placed AWSs east of Kangerlussuaq in the melt zone in an east-west section. These stations complement the weather station transect monitored by the Institute for Marine and Atmospheric Research Utrecht (IMAU) group in the Netherlands. As a result, the Kangerlussuaq part of the Greenland Ice Sheet has the highest density of weather stations, which allow high resolution temporal surface mass budget variability studies. The weather stations have performed well since the installation, providing good temporal data coverage. Future AWS work includes ice sheet mass budget modelling, which is necessary to calculate the surface melt water production.

SPA also manages a GPS network covering the Russell Glacier Catchment (14 GPS stations including a base station situated in front of the Russell Glacier). The majority of these stations have been running since 2007. The stations are being upgraded and power management regulated to decrease data acquisition interruptions. Data processing of the GPS velocity data indicates that velocity increases tend to coincide with the timing of the peak melt. Future work will involve data processing and revamping of the GPS network.

In order to obtain ice thickness information, which will aid in identifying englacial hydrological features and characterizing basal hydrological conditions, a deep-look radar system is being used. Ongoing work includes the deployment of three different radar systems including: 1) a low-frequency impulse radar system to be used for catchment-scale mapping of bed properties and bed elevation; 2) a continuously logging radio-echo sounding system to be used for studying the temporal evolution of basal hydrology; and 3) a Frequency Modulated Continuous-wave (FMCW) radar system for detailed high resolution studies around supraglacial lakes and moulins.

In 2010, SPA also carried out passive and active seismic investigations in order to identify and characterize: 1) englacial hydraulic processes; 2) sub glacial hydraulic transients; 3) basal motion triggered by the ingress of surface meltwaters to the glacier bed; and 4) deeper seismic activity related to tectonic processes in the geosphere. The obtained data is providing support for numerical models on ice sheet hydrology and the rheological controls on melt water routing.

Dye and electronic tracer studies were carried out in the Russell Glacier Catchment (RGC) at distances from 2 to 23 km up on the ice margin and revealed routed and pressurized englacial and sub glacial conduits. Further tracer studies are planned to constrain the hydrological flow paths for melt water draining in this area.

Sub-project B Activities

SPB's objectives included in situ measurements of the sub-glacial hydrological conditions of the Greenland Ice Sheet and conducting numerical modelling experiments focused on ice-sheet and basal conditions. This will provide information about the ice sheet basal boundary that can be used in groundwater models. SPB has successfully drilled 13 boreholes through the ice, totalling 1000's of meters in combined length. Ice thickness increases from the margin, and to-date, holes have been drilled through 150 m of ice, reaching the base of the ice sheet. Five kilometres up-ice from the margin, 2 boreholes of over 700 m have been drilled through the ice towards the base.

Some published modelling studies suggest that the centre of the Greenland Ice Sheet is cold-based whereas the margin is warm-based, other modelling work suggests that the entire ice sheet is at the pressure melting point at the bed. However, field results from additional ice drilling campaigns (i.e. GRIP and GISP) indicate that the bed is partly frozen. To investigate further the thermal properties of the bed, SPB is undertaking a combination of point-measurements and modelling activities. Investigation of the hydrological state of the ice bed is done through water pressure measurements (over time and space) and evaluation of bed cover and water composition. SPB is undertaking a modelling project to further investigate the basal thermal conditions in more detail within the Greenland Ice Sheet study area. SPB has also completed 3D geometry and flow field ice sheet scale models of the Greenland Ice Sheet and collected multiple data sets to be able to constrain boundary conditions [3].

Sub-project C

As part of SPC, a literature review of hydrogeology and hydrogeochemistry in the Greenland Analogue Project study area was completed [4]. During the 2009 field season, SPC drilled two cored boreholes to: 1) obtain knowledge about the permafrost conditions close to the ice margin; 2) demonstrate the presence of a talik under a lake; 3) collect core material for geological and fracture studies; and 4) provide groundwater sampling and hydraulic testing opportunities.

The inclined borehole drilled to intersect the talik beneath a lake close to the ice margin (DH-GAP01, 'talik borehole') reached 191 m vertical depth, and the second inclined borehole drilled to obtain information about the depth of permafrost at the ice margin (DH-GAP03, 'permafrost borehole') reached 320 m vertical depth. The DH-GAP01 borehole was instrumented with a U-tube system and a DTS-cable (distributed temperature sensing), which has allowed for ongoing water sampling and P/T/EC (pressure, temperature and electrical conductivity) monitoring. The DH-GAP03 borehole is equipped with a DTS-cable. Results from the down hole probes (eg. electrical conductivity) suggest that the talik borehole water is significantly different compared to the lake water, which was used as drilling fluid. The analytical results for groundwater samples from the talik borehole (DH-GAP01) suggest that a chemically distinct reservoir exists under the Talik Lake.

The DTS investigations enabled temperature profiling of the two boreholes. Steady state temperature profiles were obtained from both boreholes. These profiles confirm that the talik borehole penetrates a talik and that the permafrost borehole did not penetrate the permafrost but that the depth of permafrost at the DH-GAP03 site is close to 335 meters. In order to understand the thickness of the permafrost and to investigate the existence of taliks under lakes, the DTS temperature data was fed into a 2D numerical heat transfer model. From the modelling work it can be concluded that the permafrost in the field area is thick (more than 300 m) and that lakes in the region with a diameter greater than 100 meters likely support taliks beneath.

Logging of the two borehole cores indicated that the dominant rock types in the area are feldspar-rich gneisses interlayered with mafic, amphibole-rich gneisses and pegmatites, suggesting that the bedrock is generally comparable to metamorphic sites in Scandinavia and Canada. Fracture mineralogical samples were collected from the cores, and calcium, $\delta^{18}O$ and $\delta^{13}C$ isotope analyses are being undertaken to contribute to interpreting the source waters of fracture minerals, which will add to the understanding of the hydrogeochemistry of the glacial system.

In addition to analysis of water and core from the boreholes, a pingo spring located on a sediment plain at the margin of the ice sheet is also under investigation. This spring was instrumented with drive-point piezometers to allow for head monitoring and water sampling. The pingo system provides a conduit through the frozen ground and the analytical results suggest that the pingo water is chemically distinct from lake water and water collected from the borehole (DH-GAP01).

On-going SPC field activities continue to focus on investigations of the talik and permafrost boreholes, as well as the pingo spring, with the collection of water and gas samples for chemical, isotopic and microbiological analyses (Figure 3). Water-rock interaction studies using core from DH-GAP01 and DH-GAP03, and geologic mapping and logistical planning for the drilling of a deep (to repository depth, ~500 m) borehole under the margin of the ice sheet are underway. The deep borehole will be logged using a Posiva Flowlog (PFL), and then instrumented to allow for the measurement of temperature, pressure, electrical conductivity, transmissivity of open fractures and hydraulic head. Core and water samples from the deep borehole will be collected.

Figure 3. Collection of water samples for microbial analysis from borehole DH-GAP01.

1.4 Ice sheet and groundwater flow modeling

Ice sheet modeling

As part of the GAP project, ice sheet modeling is being undertaken by both SPA and SPB. These modeling activities will improve understanding of glacier catchment response to variable inputs of melt (seasonal, diurnal and draining of lakes on the ice surface). The influence of englacial water storage and the surface-to-bed transition times will be investigated. In addition, modeling of the Russell glacier catchment in the GAP study area under future climate projections will be undertaken.

Regional groundwater flow modeling

Within the framework of the GAP project, a regional groundwater model under ice sheet conditions was developed [5]. The aim and outcome of the flow modelling is described here. This model integrates the currently available data and information related to topography, ice thickness, talik location and ice margin position, as well as, analogue data for boundary conditions, hydraulic parameters, permafrost distribution and deformation zones derived from previous studies [5]. Figure 4 illustrates the conceptual model of the groundwater system. Figure 5 shows the location of the modelled domain, where the longest dimension of the model extends about 200 km on the ice sheet and about 50 km downstream of the ice margin. During the ongoing collection of field data, scoping calculations have been performed using the DarcyTools program in order to evaluate the current conceptual model for groundwater flow under ice sheet conditions, as well as to provide some guidance to the field investigations.

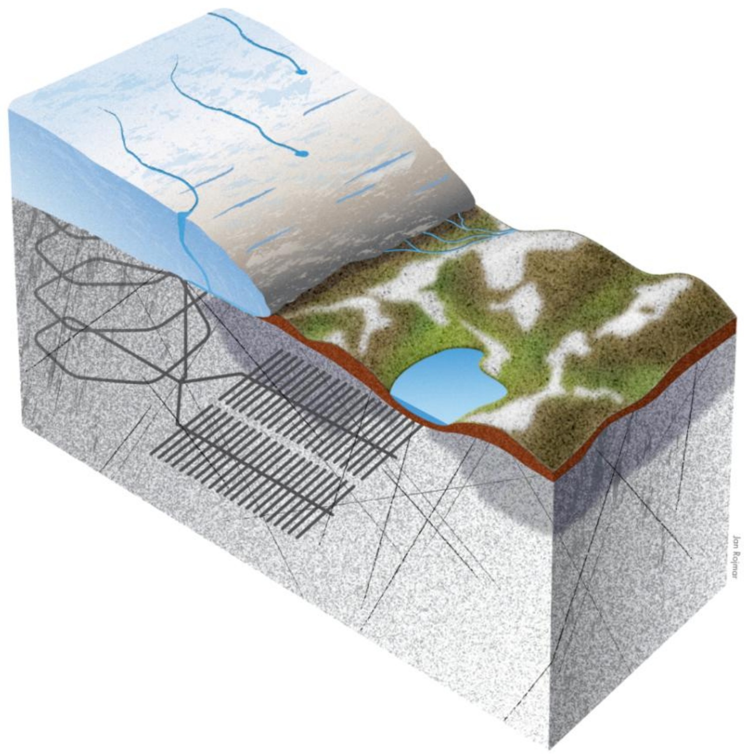

Figure 4. Conceptual model for the groundwater flow system under ice sheet conditions, with talik and permafrost (in dark grey). Illustration by Jan Rojmar.

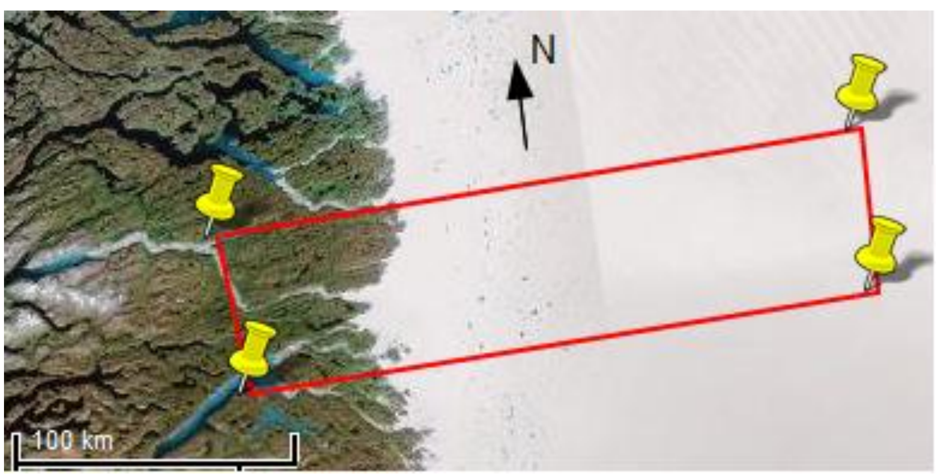

Figure 5. Location of the model domain (red rectangle) with a domain surface of about 250 x 60 km^2.

Conceptually, the groundwater system is considered to be governed by infiltration of glacial melt water in the fractured crystalline rocks in the presence of permafrost and taliks. The geological medium with conductive deformation zones was modelled as a 3D continuum with five hydrogeological units whose hydraulic properties were described using a stochastic simulation method. Based on glaciological concepts, a stochastic model was proposed for describing the sub glacial permafrost distribution in correlation with bed elevation. Numerical modelling of groundwater flow was performed at regional scale under steady state conditions for various sensitivity cases that included variations in boundary conditions and permafrost distribution. These scoping calculations were done as a first step towards data integration and groundwater flow system understanding under realistic ice sheet conditions in Greenland and may serve as a base for future modelling activities.

CONCLUSIONS

The Greenland Analogue Project is a four-year (2009-2012) field and modeling study of the Greenland ice sheet and subsurface conditions, being undertaken collaboratively by the Canadian, Swedish and Finnish nuclear waste management organizations (NWMO, SKB and POSIVA, respectively). The GAP includes three sub-projects (SPA, SPB and SPC), each with specific individual objectives, but which collectively contribute data and process understanding to the overall GAP objective. To-date, extensive field and modelling activities have been conducted, as described herein, as part of the sub-projects and will continue for the duration of the project. The on-going study of the Greenland ice sheet will allow us to increase our understanding of hydrological, hydrogeological and geochemical processes during glacial conditions.

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