High Lake Permafrost Comparison Site: Permafrost Phase IV

NWMO TR-2009-11 **July 2009**

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ABSTRACT

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Report No.: **NWMO TR-2009-11**
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Abstract

The aim of the PERMAFROST project (a collaboration with the Geologic Survey of Finland (GTK), Posiva, AKB, NASA, and OPG) is to further advance the scientific understanding of permafrost and its role in influencing flow system evolution over geologic timescales. The first three phases of the PERMAFROST project were conducted at the Lupin Mine site in Nunavut Canada. Results of Phase IV, conducted at High Lake, Nunavut, are described here.

Phase IV of the project aimed to obtain fluid samples from beneath a permafrost layer that has not been impacted by sub-permafrost mining activity. A borehole drilled previously at the site (borehole HLW 03-28) was extended and a deep borehole assembly (DBA) with a modified u-tube water extraction device was utilized to transport groundwater from below the permafrost to the surface for collection and analysis. Freezing of the borehole prevented collection of some planned samples, and required the use of drilling brine. Samples were collected from water bailed from the borehole and purged from the U-tube, and the chemical and isotopic compositions of these samples were determined. The DBA allowed temperature and pressure measurements to be obtained and hydraulic conductivity to be estimated (2×10^{-11} m/s). Surface and talik water samples were collected and chemically and isotopically characterized. The crush and leach technique was used to extract fluids from sections of core selected from throughout the length of the borehole column. For conservative ions, such as Cl and Br, compositions measured using crush and leach are likely representative of matrix fluid compositions. Chemical and isotopic analysis of waters collected during borehole bailing (2006) and U-tube purging (2007) suggest that the samples may be strongly impacted by drill brine contamination. This is further supported by tracer analysis (uranine and tritium) of the U-tube samples, which gives quantitative estimates of 37% to 100% drill brine contamination in the U-tube samples. However, even with the significant influence of drill brine on these samples, chemical and isotopic results can be compared to data collected in Phases I to III of the PERMAFROST project, and similarities between the High Lake site and the Lupin site are observed. In addition, trace amounts of hydrocarbon gases were detected and analyzed from two of the U-tube samples, and the ratio of methane to ethane and propane suggests the gases were not produced bacteriogenically. Carbon and oxygen stable isotope data of fracture calcites at High Lake are similar to previously reported fracture calcite isotopic values for Slave Province.

While samples collected in this study were impacted by drill brine contamination, the study demonstrates the potential for the deep borehole assembly approach to provide good quality chemical samples, provided a method for preventing the sample lines from freezing can be developed.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is responsible for implementing Adaptive Phased Management, the approach selected by the Government of Canada for the long-term management of used nuclear fuel waste generated by Canadian nuclear reactors (NWMO 2005). The ultimate objective of Adaptive Phased Management is centralized containment and isolation in a suitable geological formation in either sedimentary or crystalline rock. Over the long time frames for which a Safety Case for a deep geologic repository for used nuclear fuel must assess repository performance, glacial and peri-glacial conditions may influence the thermal, hydraulic and mechanical boundary conditions at repository depth. The purpose of the international PERMAFROST project (a collaboration with the Geological Survey of Finland (GTK), Posiva, SKB, NASA and OPG) is to further advance the scientific understanding of permafrost and its role in influencing flow system evolution over geologic timescales.

The PERMAFROST project was initiated in May 2001 in Helsinki, Finland. During the first three phases of this project, work program activities were focused at the Lupin Mine site in Nunavut, Canada, situated approximately 1200 km north of Edmonton in an area of continuous permafrost that extends to a depth of 540 m. Phase I was a reconnaissance level investigation, which relied upon existing and readily available mine site information, preliminary surface-based geophysical surveys and geochemical sampling at existing boreholes to develop an understanding of the occurrence and geologic and hydrogeologic setting of permafrost. Phase II PERMAFROST activities began in fall 2002, and were focused on the collection of representative geologic and hydrogeologic information to further describe the groundwater flow system and permafrost geometry. Phase III activities included further characterization of waters at the base of the permafrost, in fractures and within the matrix (pore fluids), further interpretation of the hydrogeochemical data and synthesis with other geologic/hydraulic information into a preliminary conceptual model for the Lupin Mine site, and groundwater modelling and further hydraulic head measurements to determine nature of the unsaturated zone observed beneath the permafrost at this site. Also, the potential for the existence of talik structures, unfrozen zones through permafrost, was investigated in Phase III using ground penetrating radar (GPR) soundings.

Data collected during Phases I-III suggest that mining activities have impacted the hydrogeochemical conditions at the Lupin Mine. The chemical compositions of groundwaters collected from within the permafrost suggest mixing between the resident groundwaters and drilling brines. Elevated nitrate concentrations measured in these groundwaters are thought to be the result of mixing with residual Amyl nitrate used for blasting in the mine. In addition, the existence of an unsaturated zone at the base of permafrost is attributed to drawdown as a result of mine dewatering activities. The presence of saline waters or brines at high pressures below permafrost has been previously reported during drilling for hydrocarbon resources in permafrost environments. The findings from Phases I through III at the Lupin Mine (Ruskeeniemi et al. 2002, Ruskeeniemi et al. 2004, Frape et al. 2004, Stotler et al. 2008) revealed that at this particular site, there is very little water close to the base of the permafrost, possibly as a result of mining activities. Water samples from the base of the permafrost are brackish (approx. 5 g/L TDS), Ca-Na-Cl-SO_4 and Na-Cl type waters with low tritium values (<0.8 TU), indicating that there is no recent water component in either water type. Deeper groundwaters (>800 m) are Na-Ca-Cl or Ca-Na-Cl type waters with a wide range of total dissolved solids contents from 2 to 36 g/L. Gases associated with these deep groundwaters are predominantly methane, with ethane and propane as minor constituents. Comparison of the isotopic compositions of the gases with gases from crystalline Shield environments and from sedimentary environments where permafrost extends to depths of 640 m (Lorenson et al. 1999) suggests that the gases associated with the deep groundwaters at Lupin have a thermogenic origin. These gases were most likely derived during low pressure, high temperature metamorphism of the original sediments several hundred million to billions of years ago. There is also some evidence that these gases have been affected by methane hydrate formation.

In Phase IV of the PERMAFROST Project, hydrogeochemical investigations began at a new permafrost-impacted site at High Lake, Nunavut, Canada (Wolfden Resources, now Zinifex Ltd.). The research was carried out in co-operation with the Geological Survey of Finland, the Indiana-Princeton Astrobiology Initiative (IPTAI) team of the NASA Astrobiology Institute and Lawrence Berkley National Laboratory. The objectives of Phase IV included:

i) Obtain fluid samples from beneath a deep permafrost layer that has not been impacted by subpermafrost mining activity, for comparison with information collected from the Lupin Mine during Phases I through III of the PERMAFROST Project;
ii) Obtain rock cores from within and beneath the deep permafrost layer for mineralogical and pore water composition determinations;
iii) Determine the composition and isotopic abundances of gases from beneath the permafrost and gases trapped as hydrates from within the permafrost (assuming these gases can be collected);
iv) Determine the composition, origin and residence time of the subpermafrost water, and of the porewater from within the permafrost;
v) Determine whether gradients in salinity, gas concentration, pH, and redox (pe), exist at the lower boundary between the permafrost and the groundwaters below.

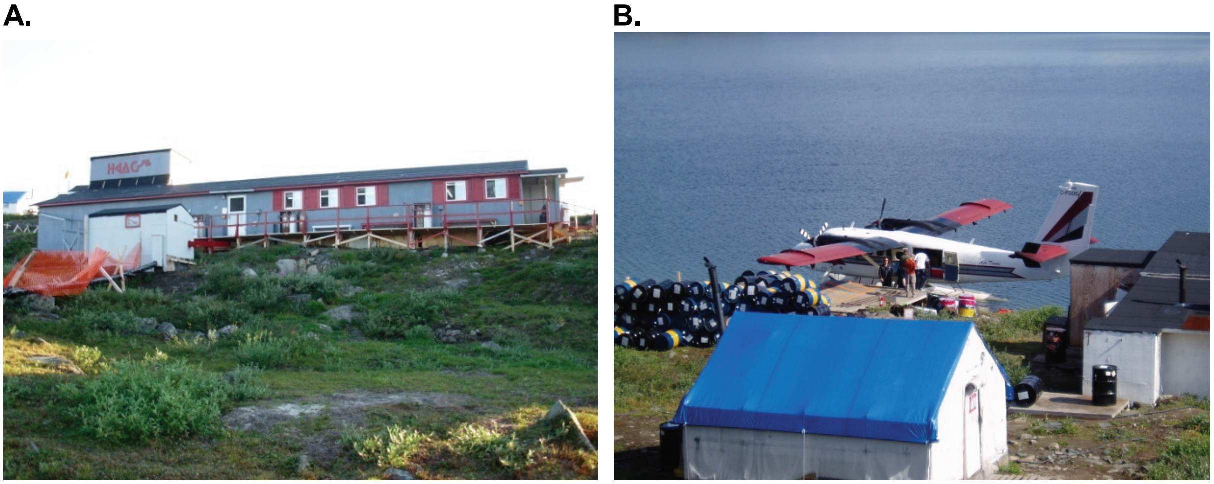
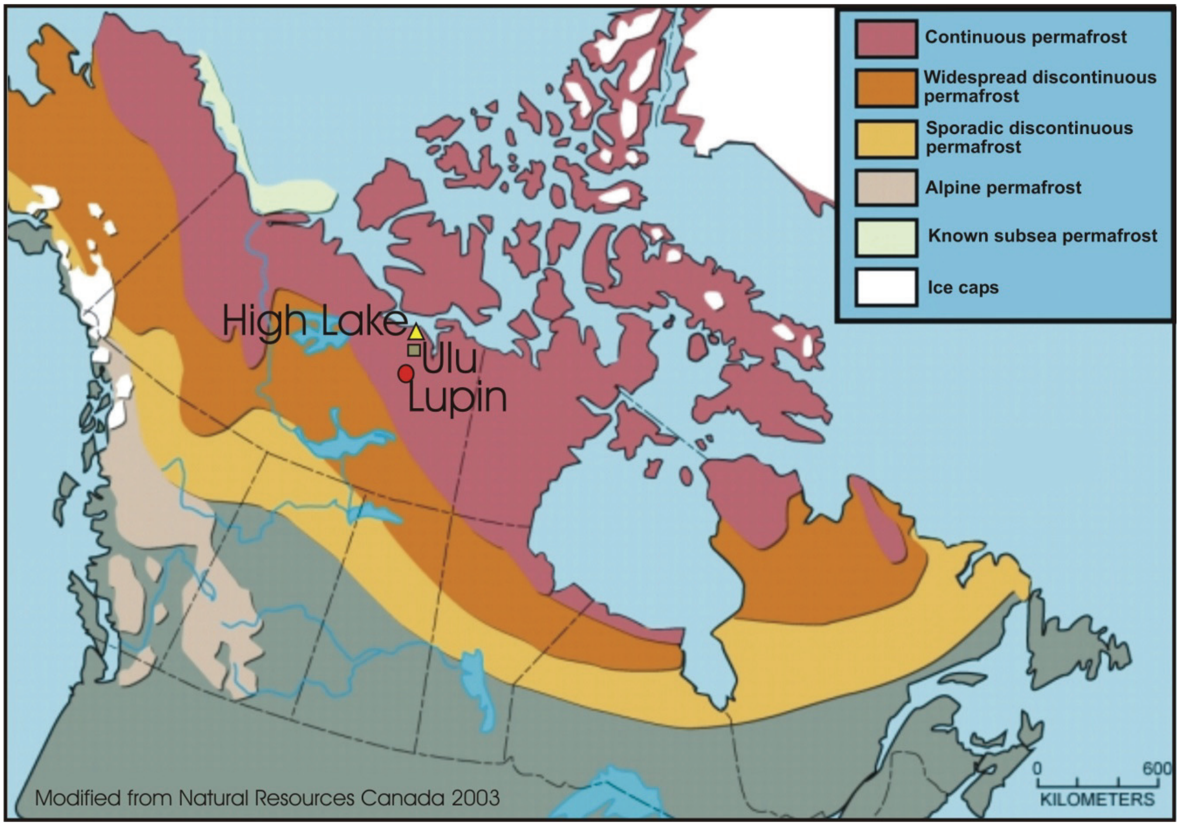


Figure 1: Facilities at High Lake. (A) Kitchen, dining hall, and showers. (B). Sleeping quarters (white tent with the blue tarp) and summer tranportation to and from the site: an Air Tindi Twin Otter float plane, service from Yellowknife.

2. SITE DESCRIPTION

The High Lake Zn-Cu prospect is located in the Nunavut Territory (67° 22’ 47” N, 110°50’ 37” W) about 550 km north-northeast of Yellowknife, NWT, 40 km south of Coronation Gulf, and 169 km north of the Lupin Gold Mine. High Lake is situated well within the zone of continuous permafrost. The deposit is currently owned by Zinifex Ltd. In February 2007, the High Lake project received a positive review by the Nunavut Impact Review Board, allowing formal commencement of the Environmental Assessment. Licenses were also issued in January 2007 by the Kitikmeot Inuit Association allowing the mining company to construct a new camp facility at High Lake and an airstrip at Sand Lake. Currently all supply and personnel transport to and from the site is by float plane or helicopter in the summer, or Hercules aircraft on a temporary airstrip in the winter. At present, only exploration and site assessment activities are occurring at the site, providing the opportunity to study groundwater in a relatively undisturbed permafrost environment.



Modified from Natural Resources Canada 2003

Figure 2: High Lake relative to Lupin and Ulu. Like Lupin, High Lake is well within the zone of continuous permafrost.

2.1 HIGH LAKE GEOLOGY

The High Lake Cu-Zn sulphide deposit is a volcanic-hosted massive sulphide (VMS) deposit located in the Archean High Lake Greenstone Belt (HLGB) in the northern Slave structural province. In addition to High Lake and Lupin, groundwaters and gases at the Con and Giant mines (located just outside Yellowknife), also located in the Slave Province, have been previously studied (i.e Frape et al. 2003, Bottomley at al. 2005, Frape and Fritz 1987, Sherwood Lollar et al. 1993a,b). These sites are located in the discontinuous permafrost zone, and results from the earlier studies will be discussed in comparison to results from High Lake; as such a regional view of Slave Province geology is warranted as part of a discussion of the High Lake deposit.

2.1.1 Regional Geology

The Slave Province is broadly subdivided into three geological groups: 1) pre-Yellowknife Supergroup rocks, 2) supracrustal rocks (metasedimentary, metavolcanic, and syn-volcanic plutons) included in the Yellowknife Supergroup (YKS), and 3) syn- to post- deformation granitoid rocks. Pre-YKS rocks are restricted to the western margin of the province; these rocks are geographically and temporally (between 150 and 1200 m.y. older than YKS rocks) isolated, and will not be discussed further. Approximately 65 m.y. of volcanism, from 2715 to 2650 m.y. resulted in rock outcrops in over twenty geographically separate belts, comprising 50% of the area of the province (Davis 1991).

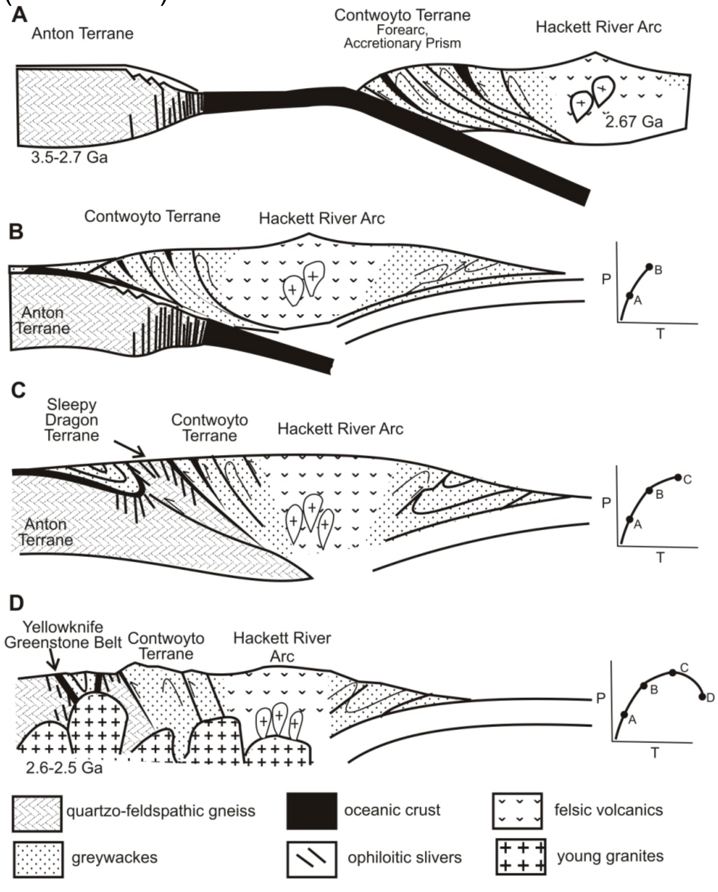


Figure 3: Early geologic history of the Slave Province. Accretion is similar to modern day island arc systems. Lupin is located in the Contwoyto Terrane, High Lake is believed to be part of the Hackett River Arc (transect shown is across southern Slave Province). From Kusky (1989).

Beneath the Yellowknife Supergroup there is Acasta basement gneiss, roughly 3.96 to 3 Ga, which is overlain by thick greywacke turbidite and basalt ranging from ca. 3 to 2.66 Ga

(Henderson et al. 1993). Most of the tectonic models proposed for the Slave Province involve single and multiple volcanic and sedimentary arc complexes which were formed by an eastward subduction-acceretion. The regional geology of the Slave Province is characterized by low pressure and high temperature regional metamorphism (Henderson et al. 1993).

2.1.2 High Lake Greenstone Belt

The High Lake Greenstone Belt (HLGB) is north-south striking, approximately 80 km long, typically 5-10 km wide in the north and up to 25 km wide in the south (Hoffman 1992). Steeply dipping intermediate to felsic volcanic-volcaniclastic successions and slate-greywacke sedimentary sequences dominate, ranging in age from 2705±1 to 2614 ±3 Ma, all of which are intruded by late Archean granitic batholiths (2.62-2.58 Ga). The HLGB lies on the boundary of the “Contwoyto Terrane” and the “Hackett River Arc”. Rocks in the Northern part of the HLGB tend to be of Yellowknife supergroup age, while those in central domain are younger, closer in age to the granitic intrusions (O’Keefe 1996). The northeast trending Anialik River Greenstone Belt is immediately west of the HLGB.

The HLGB lies within a zone of chlorite or greenschist facies grade metamorphism, which is surrounded to the north and south with an andalusite zone containing amphobolite facies grade metamorphism (Henderson et al. 1995). The presence of chlorite results in a metamorphic grade that is low throughout the centre of the HLGB, with no visible higher contact observed within the belt.

Henderson et al. (1995) mapped the HLGB along a 100 km stretch of land using U-Pb zircon dating of the volcanic rocks to determine the distribution of the geologic material. This distribution of geologic material helped to determine the mineral occurrences and distinguished three distinct geologic domains (Figure 4): a western and eastern volcanic domain and a central mixed domain. All of the domains are surrounded by granitic plutons and batholiths dated roughly 2.62-2.58 Ga (Henderson et al. 1995). The distinct and abrupt change between the felsic intermediate and mafic volcanic rocks cannot be easily explained by folding and faulting formations of the domains (Henderson et al. 1994).

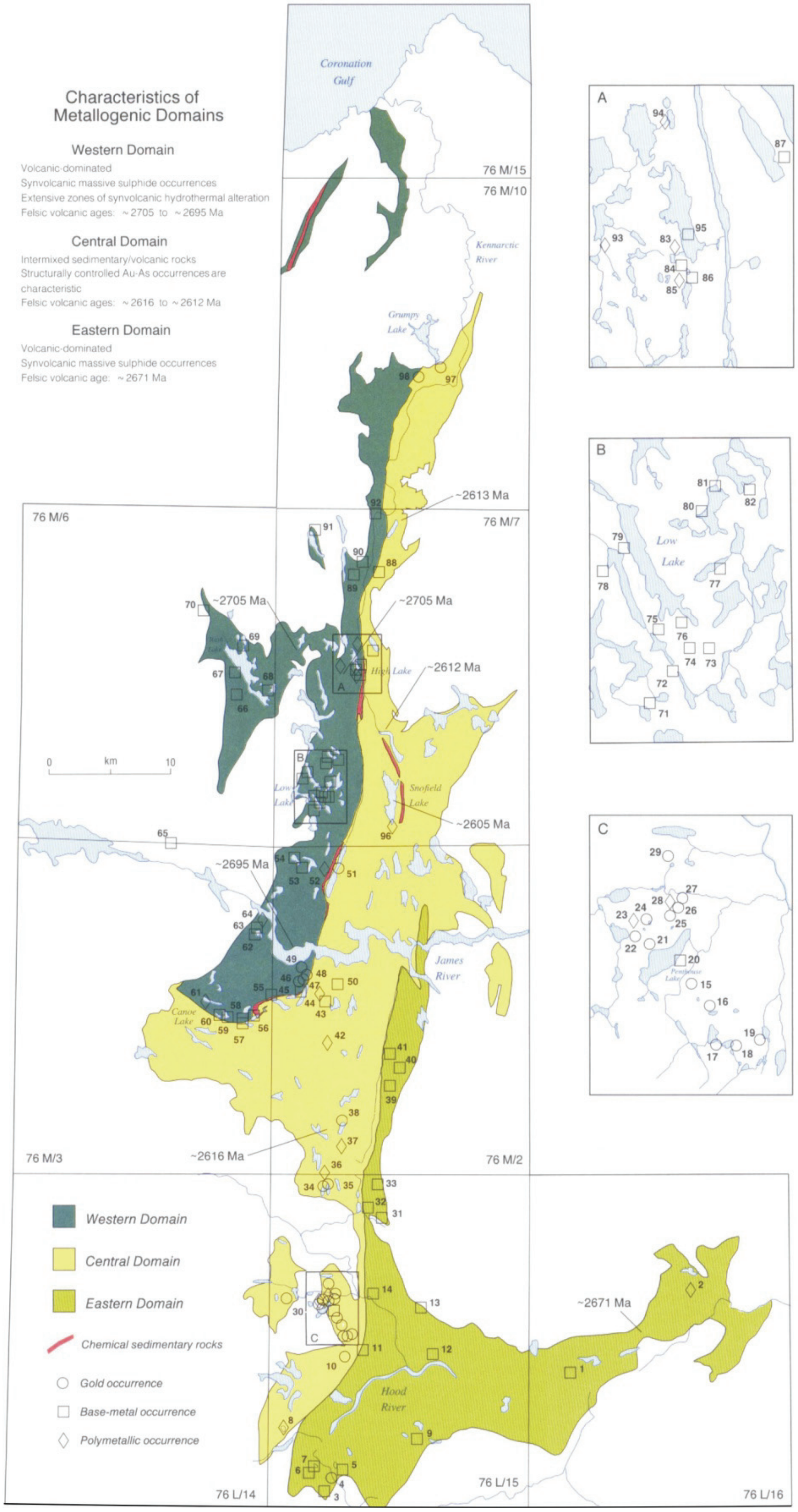


Figure 4: Map of the High Lake greenstone belt showing the location of the study area (Box A), metallic deposits (Box B and C), and the western, central, and eastern domains. Modified from Henderson et al. (2000).

2.1.2.1 Western Volcanic Domain

The western domain contains older felsic volcanic rocks (roughly 2.70 Ga) and volcanoclastic rocks (Henderson et al. 1995), with areas of minor mafic volcanic rocks. With the presence of quartz-sericite-chlorite bands possibly caused by hydrothermal alteration, the felsic volcanic rocks are considered greenschist grade facies. Numerous sulphide occurrences within the domain show the presence of gold within the region. The High Lake deposit is located within this domain (Petch, 2004).

2.1.2.2 Eastern Volcanic Domain

The eastern domain is composed of intermediate and mafic (basaltic, andesitic, and dacitic) rock flows and tuffs, aged to ca 2.67 Ga. The lack of sedimentary rocks in this domain indicates the occurrence of only one cycle of volcanism (Henderson et al. 1995).

2.1.2.3 Central Mixed Domain

The central domain contains the youngest volcanic rock within the HLGB, ca. 2.62 Ga, which has contact between greywacke, siltstone, and graphite-sulphidic slate sedimentary rocks. The sedimentary rocks extend as deep as 10 km with no evidence of unconformities within the mixed igneous and sedimentary layers of the domain (Henderson et al. 1995). The sedimentary rock layers of the central domain are known to be interlaced with felsic and mafic volcanic flows (Petch, 2004).

The HLGB also contains metasedimentary rocks in the northern section which form elongated bodies. These bodies are about 9 km NNE of the High Lake deposits, at the northernmost reach of the belt (O’Keefe 1996). The metasedimentary rocks are composed of light grey metawacke and siltstone that is medium to dark grey in colour, which are interbedded with thin beds of dolomitic marble and black granite.

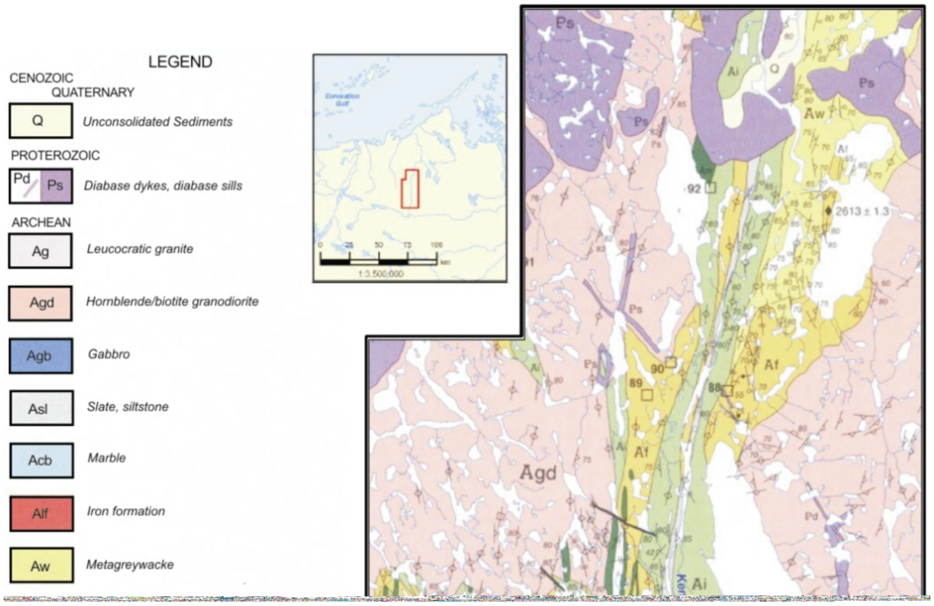


Figure 5: Geologic map of the central part of the HLGB. From Henderson et al. (2000).

2.1.3 Structural Formation and Deformation

The structural history of the belt is polyphasic and the structural fabrics are heterogeneously developed (Henderson et al. 1994). Henderson et al. (1993) determined four sets of structures within the supracrustal rocks of the belt. The first set of structures is a deformation fabric caused by a parallel-bedding foliation (S_1). The second structure is a deformational event (D_2) which resulted in steeply plunging map scale folds, with no axial planar cleavage. The third structure

(S_3) is the main one that over prints two folds (F_2 & F_3). The fabric is primarily developed and ubiquitous in the metasedimentary rocks and is weakly represented in area plutons. The final structure is a weakly developed fabric (S_4) that is of an unknown age (Petch 2004). The rocks within this region show an early deformation defined by folds with limbs that were transected by structural cleavages (Henderson et al. 1994). A summary of the structure of the region is given in Table 1 below:

Table 1. Summary of the Structural History of the HLGB (From O'Keefe 1996)

Structures		*Metamorphism*
Cleavage	*Folds*	
S_1 - layer parallel cleavage		- mainly greenschist characterized by Chl, Mu +/- Bt* - relict Crd^{+} present (early event) - amphibolite grade in the Ulu structure (Amp, Crd, And)** - locally Grt (in Fe-fmtn)$^{++}$
	F_2 – tight-isoclinal steeply plunging, east-west closing folds	
S_3 – NNE striking continuous cleavage; dominant structure in belt	F_3 - mesoscale folds with S_3 axial planar cleavage	
S_4 - Subhorizontal crenulation cleavage restricted to the Ulu structure		

*Chl = chlorite, Mu= muscovite, Bt = biotite
$^{+}$Crd = cordierite
**Amp = amphibolite, Crd= cordierite, And = andalusite
$^{++}$Grt = garnet, Fe-fmtn = iron formation

There are a few distinct structural features; the western domain contains flattened clasts that were created by the main northeast striking cleavage which estimates the fabric as being S_2, while the central domain is structured with a S_1 cleavage that is axial-planar north to south with steeply plunging folds (Henderson et al. 1995).

2.1.4 Mineral Occurrences in High Lake Greenstone Belt

The High Lake deposit is a volcanic-associated massive sulphide deposit, with characteristics similar to other submarine volcanic sequences throughout the world (Petch 2004; Franklin et al. 1981). Gossans, natural acidic drainage formations resulting from surface oxidation of the ore (Figure 6), are readily visible in satellite images. They have formed during the postglacial period in the active layer on top of the permafrost.

The High Lake deposit consists of three economic zones, "AB", "D" and the "West Zone", of polymetallic massive sulphide deposits, some of which are visible as gossans (Figure 6). These gossans consist of massive and stringer chalcopyrite+ pyrite and sphalerite, with lesser pyrrhotite, galena, gold, and silver (Henderson et al. 1995). In total, the HLGB contains almost 70 deposits with 39 visible gossans (Henderson et al. 1994).

Figure 6: Gossan within the D-zone of HLGB.

Work conducted in Phase IV of the PERMAFROST project was completed in the vicinity of the D-zone, a banded polymetallic VMS deposit composed of pyrite, chalcopyrite, sphalerite, magnetite, and galena. D-zone geology is summarized in a 2006 report (Gartner Lee 2006a). The D-zone strikes 030° and dips steeply to the west-northwest. Four main lenses of mineralization are found in the deposit - the largest is 150 m in length, 320 m down dip, and is up to 35 m thick. The High Lake Fault truncates the north end of the deposit, a granodiorite intrusion cuts off the southern portion. Altered felsic ash lapilli tuffs, trending north-northeast, dipping steeply to the west, host the deposit. The western portion of the deposit is zinc-rich, while the eastern portion is copper rich.

The AB zone is just north of the D-zone. The AB zone contains a high percentage of metavolcanic rocks (felsic is the most common) with smaller amounts of calc-alkaline, intermediate dikes, diabase dikes and metasedimentary rocks (Petch, 2004). The main sulphide minerals within the AB zone are pyrite, pyrrhotite, chalcopyrite and sphalerite resulting in the sources of gold, silver, and zinc for extraction (Petch, 2004).

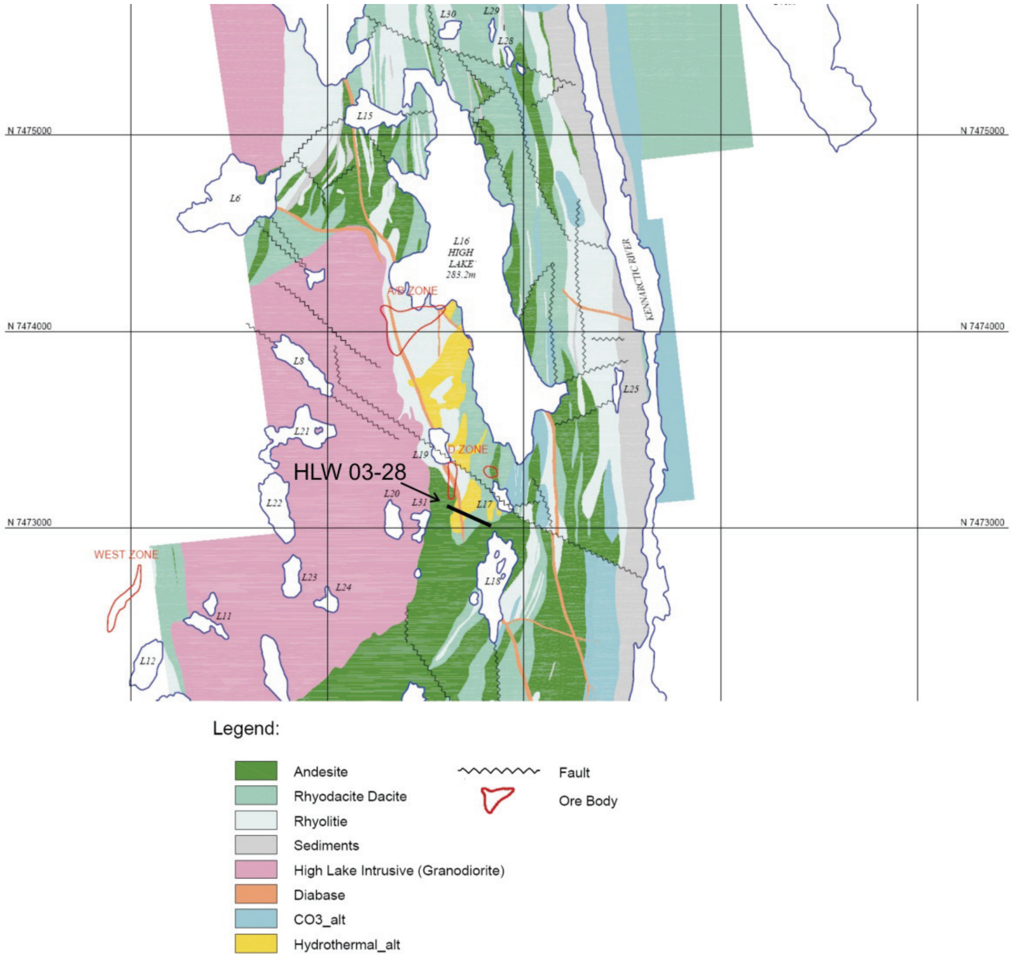


Figure 7: Geology of the study area, with the surface trace of the drilled borehole. "Alt" stands for alteration. Modified from Gartner Lee (2006a).

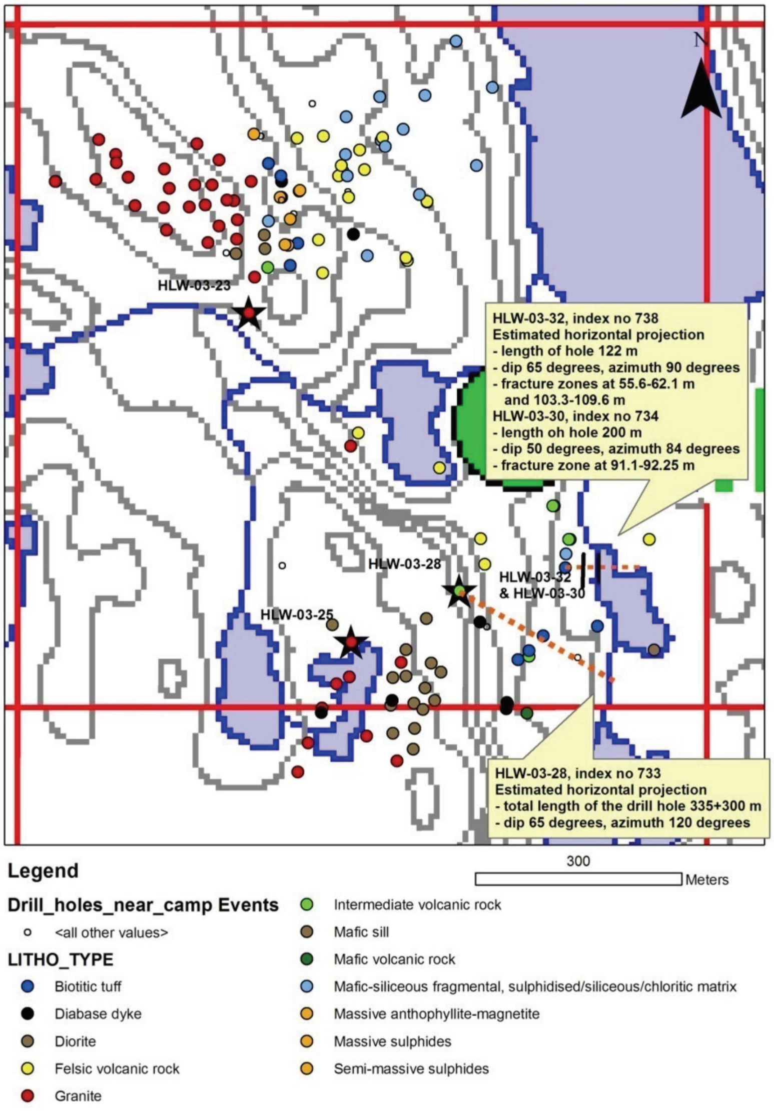
3. PHASE IV ACTIVITIES

3.1 EXTENSION OF BOREHOLE HLW 03-28 (2006)

Phase IV of the PERMAFROST project aimed to work in a relatively pristine, undisturbed permafrost environment, making it necessary to drill a borehole from surface to investigate subsurface conditions. To keep drilling costs to a minimum, it was decided to extend a shorter borehole previously drilled by Wolfden Resources. A careful survey and analysis of available boreholes at High Lake was conducted by Matti Talikka of the Geological Survey of Finland. Criteria used in borehole selection are:

- Borehole length as completed by Wolfden Resources of less than 300 m to ensure permafrost has not been drilled through. This is necessary because boreholes drilled by the mine use an anthropogenic brine as drill fluid to keep boreholes and drill fluid from freezing in permafrost sections during drilling.
- Drilled on a 59° to 90° angle from horizontal to ensure the borehole is perpendicular to the bedding planes .

- Old core available for inspection and analyses.
- Few, if any, other boreholes completed through the permafrost nearby to minimize disturbances to the study area.
- Within 1 km of the camp to ensure access and lower helicopter costs.
- Away from major mineral deposits to allow for the possibility of long term monitoring.
- Casing in place to ensure the borehole could be found for drilling.



HLW-03-32, index no 738
Estimated horizontal projection
- length of hole 122 m
- dip 65 degrees, azimuth 90 degrees
- fracture zones at 55.6-62.1 m
  and 103.3-109.6 m

HLW-03-30, index no 734
- length oh hole 200 m
- dip 50 degrees, azimuth 84 degrees
- fracture zone at 91.1-92.25 m

HLW-03-28, index no 733
Estimated horizontal projection
- total length of the drill hole 335+300 m
- dip 65 degrees, azimuth 120 degrees

Figure 8: Location of three boreholes considered (denoted by stars). HLW-03-28 is shown with a surface trace of the borehole and extension. The surface trace of HLW 03-32, which indicated the presence of fractures, is also shown.

Three boreholes were initially considered: HLW-03-23, HLW-03-25, HLW-03-28. HLW-03-28, with an existing length of 335 meters (303.6 m below ground surface. Hereafter, when referring to length along the borehole from the collar, ‘m’ will be used, and ‘mbgs’ will refer to the actual vertical depth below ground surface) from the collar and dip of 65° from horizontal, was selected. The horizontal projection of HLW-03-28 with a 300 m drilling extension suggested it would extend beneath a potential N-S trending fault zone, as indicated by a line of lakes. The borehole trace would extend between two of the lakes; the northernmost of which is believed too small for talik formation. Boreholes HLW-03-30 and HLW-03-32, drilled under the northern lake, also indicated the presence of fracture zones, however the direction and orientation of the fractures is unknown. Five drill holes were located within 100 m of the HLW-03-28 drill collar. Only HLW-05-11 (482 m, dip 62°), located 80 m to the NNE of HLW-03-28, appears to extend beneath the permafrost.

Prior to the arrival of the research team, Major Drilling set a short casing to secure the top of the hole and used an NQ bit and anthropogenic brine to core out ice in the borehole. Once the bottom of the borehole was reached, they switched to fresh water from Core Shed Lake which was heated to ~70°C by oil heaters and circulated through the borehole for ~7 days prior to the initiation of coring. The purpose of this was to flush out existing drilling brine and warm the borehole and surrounding rock. Coring was completed with an NQ3 bit (75.7 mm pipe width) to allow use of PVC core liners for microbial cores.

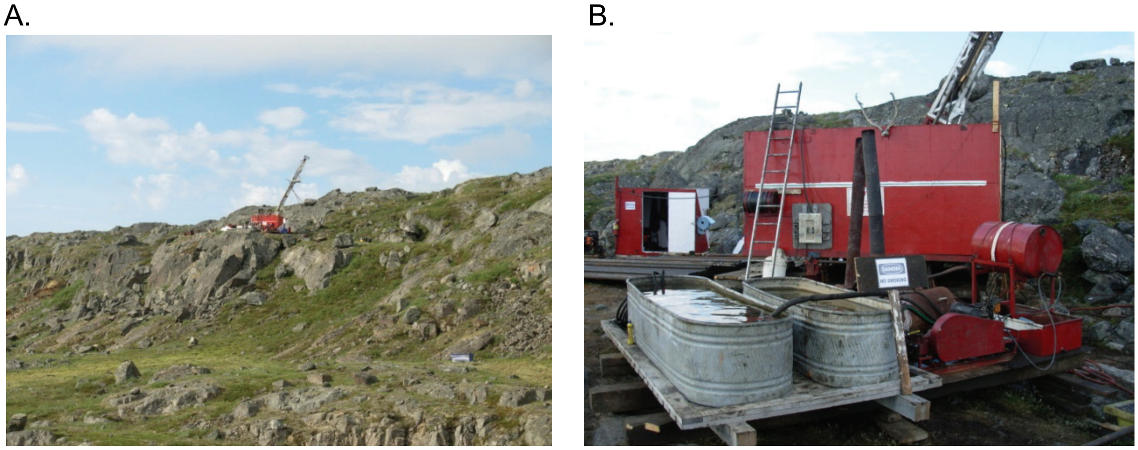


Figure 9: (A) Drill and borehole location at the top of a 15-20m cliff, (B) Oil heaters and setup used to heat drill fluid.

Throughout drilling, a 1% perfluorocarbon tracer (PFT) solution was pumped into the high pressure (~400 PSI) drilling water line at 8-10 mL min^{-1}. The drill water was pumped into the drill rods at ~30 L min^{-1}, resulting in a dilution of 3.3 x 10^{-6}. The PFT tracer was pumped into the drill water throughout the coring operation to evaluate mixing of drill water with natural waters (Pfiffner et al. 2008). Samples of drill water were collected from the sump can at the base of the drill rig for tracer and conductivity analyses with every 3-m coring run. Drilling water was not re-circulated, but was pumped to a settling pond at the top of the hill after passing through a sludge container, ensuring the PFT concentration remained relatively constant in the drill fluid.

Coring was completed when a down-hole depth of 535 m (484.9 mbgs) was reached, after drilling 200 m of additional core. Coring was considered to be complete because it was assumed that the permafrost had been penetrated, the rock became sparsely fractured and the limit of the drilling budget was reached. Because drilling ceased at 200 m rather than the initially planned 300 m, the borehole does not extend beneath the chain of lakes and the potential fracture zone. According to driller expert judgement, the base of the permafrost was located at approximately 410 m (370 mbgs). Because no temperature measurements were available from this area, the only information about the depth of permafrost was based on experience from the former drillings. Permafrost depth will be discussed further in Section 4.3. A steel casing (inner diameter 60.3 mm) was installed in the borehole to 320 m to maintain stability in the permafrost zone, where the potential for caving in several intensively sheared zones (up to 6 m in length) could have prevented future access to deeper levels. Because the frozen bedrock does not allow water flow, all sampling opportunities were utilized.

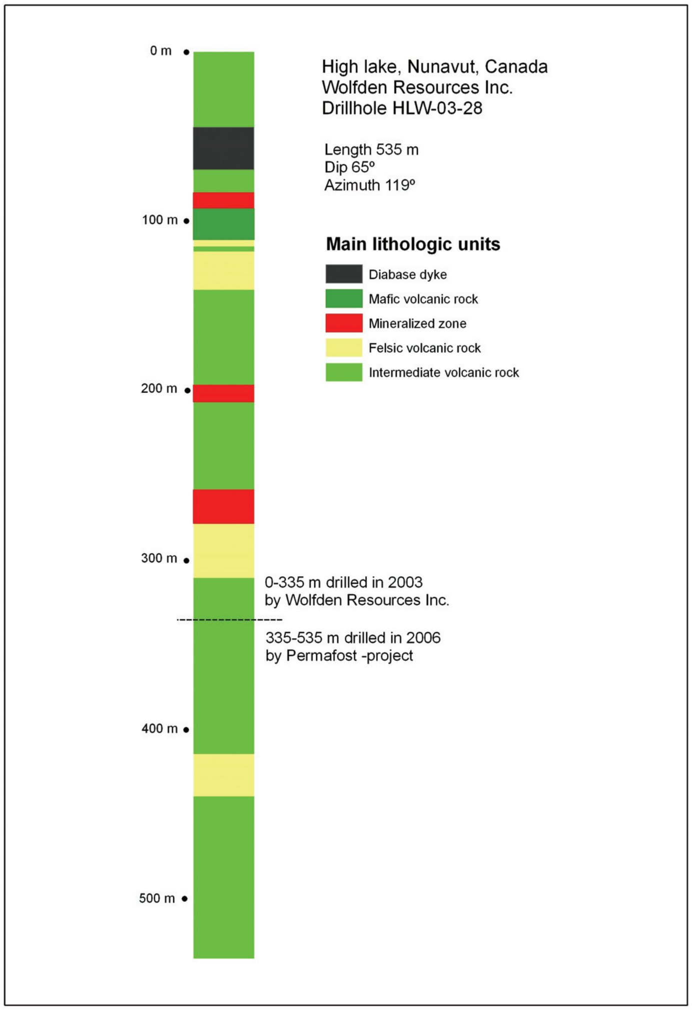


Figure 10: Geologic log of the HLW-03-28 borehole and extension. The upper 335 meters was cored by Wolfden Resources, the lower 200 meters by the PERMAFROST project team.

The lithology of the upper 335 m was logged by Wolfden Resources geologists; lithology and fractures were logged in the 200 m extension by Matti Talikka of the Geological Survey of Finland. As shown in Figure 10, the 200 m extension primarily drilled through intermediate volcanic rock.

Upon completion of drilling activities, a bailing operation was conducted to clean out as much contaminating drill water as possible and lower the water table to unfrozen conditions. An 18 L bailer was constructed by the drill foreman, Bruno Zerbin. The bailer was dropped a total of twenty-three times, removing about 400 L of water from the borehole. Water samples were collected five times throughout the process to check conductivity, pH, and temperature. Samples for chemistry and isotopes were also taken from these five bailer samples. The water level was determined to be 492 m (446 mbgs) on the 31st of July, with approximately 1 L/hr inflow, determined using a downhole conductivity probe. During retrieval of the down-hole probe, the borehole iced at ~125 m (113 mbgs). Attempts made to drill through the ice without drill fluid failed. Further work on the borehole was suspended for reanalysis of the situation and additional attempts were made to clear the borehole in the 2007 field season (Section 3.2). To date, only two diverse microbial communities have been identified in the collected drill core and water samples, however, additional communities are hoped to be obtained in future samples (Pfiffner et al. 2008).

3.2 U-TUBE INSTALLATION (2007)

Field activities from the end of July to the beginning of August 2007 focused on the opening of the existing borehole (HLW-03-28) through the permafrost to a depth of 535 m (484.9 mbgs) (Section 3.1). Upon arrival on site in 2007, ice was discovered at a depth of 2 m in the borehole, much more shallow than the ice observed at 125 m in 2006. Assuming the hole was filled with ice through the permafrost, the decision was made to drill through the ice. Drilling commenced using only the drill bit and rods which proved ineffective, and so recirculated warm water was again utilized (Section 3.1). Uranine was added into the recirculated water to act as a tracer. Cable from the tool which was lost in the borehole in August 2006 got wrapped around the drill bit and the drill string had to be removed. After removing the cable, drilling recommenced, but the loss in momentum caused the drill fluid to cool down such that the drill bit froze in place. Even though drill water of 98°C was pumped down the borehole, the return water was only 2°C. After a day of no progress thawing the drill string, a decision to introduce a salt solution into the drill fluid, with uranine still utilized as the tracer, was made after consultation with the drill foreman, Zinifex officials, and the NASA research team. Once the drill had reached a depth of 480 m, the drill rod was removed.

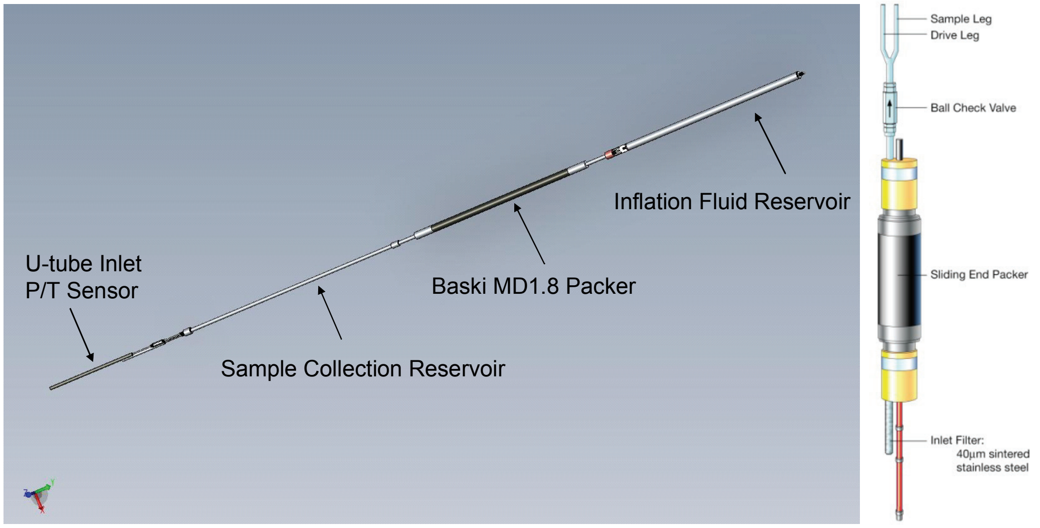


Figure 11: Cross-section of deep borehole assembly, showing each section and an inside view of the packer and sampling system.

A deep borehole assembly was installed to a packer depth of 465 m (421 mbgs). The deep borehole assembly (DBA) was designed and built by Barry Freifeld (Lawrence National Laboratory, USA), using existing research in terms of the effectiveness of a U-tube (Freifeld et al. 2005, Freifeld and Trautz 2006) and carbon dioxide sequestration (Freifeld et al. 2005) at depth. The DBA contained a pneumatic packer, U-tube sampling system with a sample reservoir and a temperature/pressure sensor line (Figure 11). Running a total length of 14.9 m, the DBA contained propylene glycol in the reservoir initially because of its low freezing point, and the packer was inflated using nitrogen from the surface. The DBA was connected to the surface by three 6.4 mm diameter stainless steel tubes connected to the packer system to inflate the packer, a drive line to force the fluid in the reservoir to move, and a collection line to collect water from the reservoir at the surface. Next to the stainless steel tubes was a heat tape to prevent the tubes from freezing and a fiber-optic cable. In addition, a cable extended through the packer to a LevelTroll temperature-pressure transducer which measured the temperature and pressure profiles using laser backscattering (i.e. Distributed Temperature Sensor, DST) within the borehole from the top of the DBA to the surface.

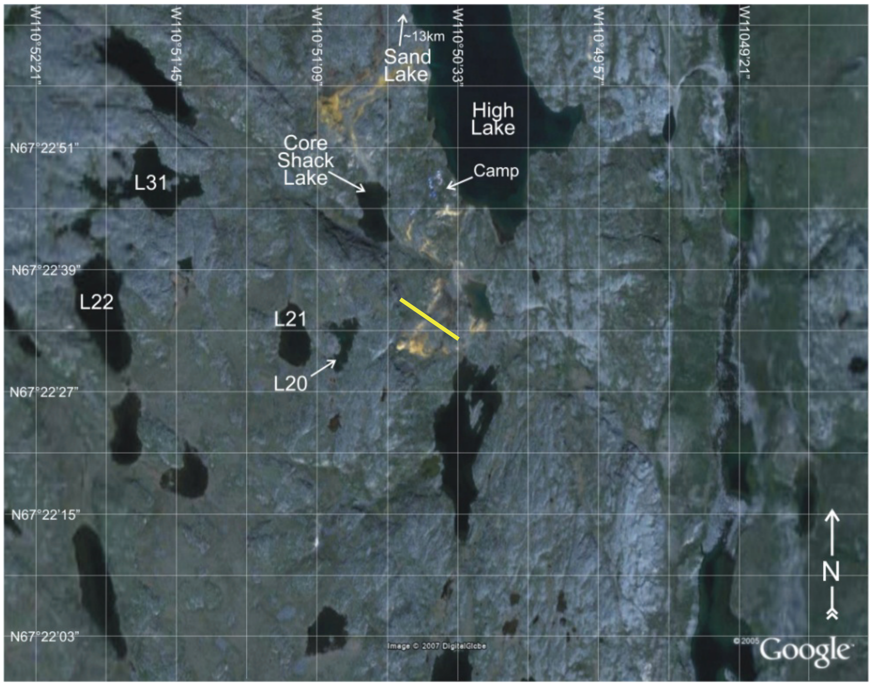


Figure 12: Satellite image of High Lake area. Surface water samples were collected from Sand Lake, High Lake, L20, L21, L22, L31, and Core Shack Lake. Water from Core Shack Lake was used as drill fluid. Approximate surface trace of Borehole HLW-03-28 is shown in yellow.

4. PHYSICAL MEASUREMENTS

4.1 HYDRAULIC CONDUCTIVITY

During sampling runs, pressure monitoring of the DBA using a pressure/temperature sensor located near the inlet of the U-tube sampling system allowed hydraulic conductivity estimates to be calculated. The U-tube sampling event corresponds to a sharp increase in pressure (over several minutes) immediately prior to a rapid decrease in pressure, as the compressed gas is vented from the sampling tubing. As fluid re-enters the well the downhole pressure rebounds. As shown in Figure 13(b), the increase in pressure occurs in two distinct phases: a slow pressure increase immediately after sampling and venting of the sample lines, which corresponds to filling the downhole sample reservoir, and a more rapid increase, which corresponds to the filling of the small diameter sampling lines that run up to the surface. The Theim solution, which assumes a homogeneous, confined radial aquifer at steady-state, was used to solve for hydraulic conductivity. Steady state was determined to be a valid assumption as the observed pressure change was linear during the filling of sample lines. The hydraulic conductivity is estimated to be 2.3×10^{-11} m/s (Table 2). This low conductivity is typical of unfractured crystalline rocks (i.e. Mazurek 2000).

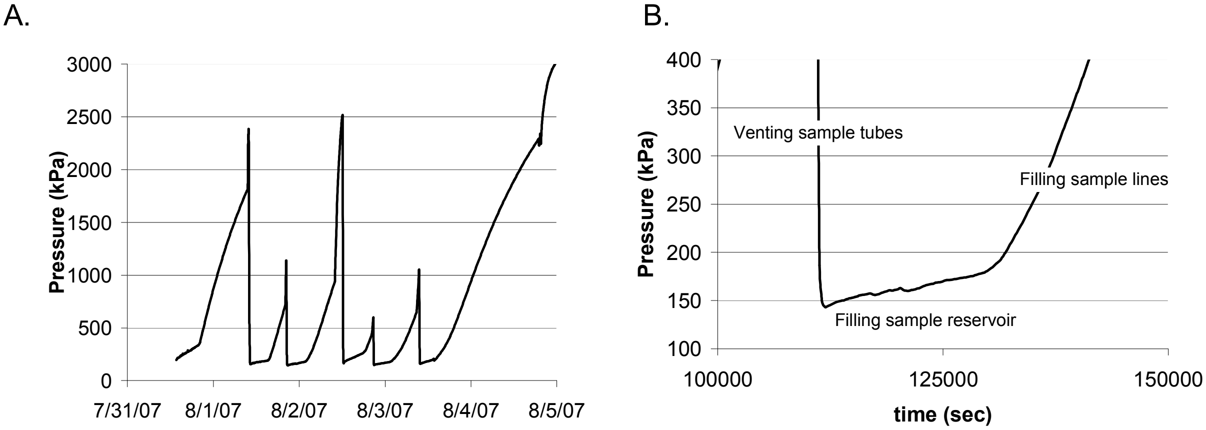


Figure 13: Pressure response during U-tube sampling events as measured near the U-tube inlet. Following acquisition of a U-tube sample and sample line N_2 gas venting, the pressure rebounds slowly as the sample reservoir fills, followed by a more rapid rebound during filling of the small diameter sample lines.

The hydraulic conductivity value estimated from HLW-03-28 at 381 to 485 m below ground surface is similar to those calculated elsewhere on the property from depths greater than 400 mbgs (Table 3, HLW-05-161 and HLW-05-168; Gartner Lee 2005, 2006a,b). The permeability tests conducted previously used a 22% calcium-chloride solution, and were not corrected for brine density effects. Therefore, the previously reported values represent an upper limit for hydraulic conductivities, although the actual permeabilities are expected to be within the same order of magnitude as those reported by Gartner Lee Ltd (Gartner Lee 2005, 2006a,b).

Figure 14: Location of boreholes where hydraulic conductivity and temperature measurements were taken (Modified from Gartner Lee 2006b). Talik water samples were also collected from BH06-T1.

Table 2. Summary of measured hydraulic conductivities (K) from High Lake. Borehole HLW-03-28 from this report, other data from Gartner Lee (2006a).

Location	K (m/s) (geometric mean)	K (m/s) (range)	Depth of Measurement
D Zone, HLW-03-28, (volcanic country rock)	2×10^{-11}	-	381 to 485 m below ground surface
High Lake talik, BH06-T1 (volcanic country rock)	6×10^{-8}	4×10^{-9} to 6×10^{-7}	28 to 120 m below lake surface
High Lake talik, BH06-T2 (intrusive diabase dike)	9×10^{-9}	5×10^{-9} to 1×10^{-7}	25 to 106 m below lake surface
West Zone, BH06-L12 talik (volcanic country rock)	6×10^{-8}	3×10^{-9} to 1×10^{-6}	15 to 77 m below lake surface
West Zone, HLW-05-161 (volcanic country rock)	6×10^{-10}	2×10^{-11} to 2×10^{-9}	440 to 700 m below ground surface
West Zone, HLW-05-168 (volcanic country rock)	4×10^{-10}	5×10^{-11} to 4×10^{-10}	440 to 900 m below ground surface

Table 3. Summary of hydraulic conductivity with depth at High Lake. HLW-03-28 analyzed in this report, other data from Gartner Lee (2005, 2006b).

Borehole	Test Number	Packer Test Interval (along borehole axis)		K
		Top (m)	Bottom (m)	(m/s)
HLW-03-28	1			2×10^{-11}
BH06-T1	1	28	43	4.88×10^{-7}
	2	43	79	9.19×10^{-9}
	3	79	100	6.59×10^{-9}
	4*	28	119.5	3.09×10^{-7}
BH06-T2	1**	25	43	3.78×10^{-8}
	2	44	64	5.18×10^{-10}
	3	64	85	2.64×10^{-9}
	4	85	106	9.84×10^{-9}
	5*	24	106	1.00×10^{-7}
BH06-L12	1*	15	36	1.29×10^{-6}
	2	33	57	7.21×10^{-9}
	3**	57	76.5	2.52×10^{-9}
	4*	21	76.5	3.86×10^{-7}
HLW-05-161	1	400	487	2.03×10^{-10}
	2	484.4	538.4	2.90×10^{-10}
	3	540.0	622.0	1.63×10^{-11}
	4	629.0	685.4	1.77×10^{-9}
	5	50.0	697.0	5.73×10^{-10}
HLW-05-168	1	400.0	571.0	6.57×10^{-11}
	2	569.0	709.0	9.03×10^{-11}
	3	568.0	796.0	5.06×10^{-11}
	4	50.0	901.0	3.51×10^{-10}

*Short-circuit suspected **Leakage

4.2 GROUNDWATER ELEVATION

The final pressure readings from the pressure sensor were 3215 kPa on Aug 7, 2007 when the research team left camp. Assuming the Aug 7, 2007 pressure reading approaches the final pressure, and that dilute water is in the borehole (Section 5.4), the equivalent freshwater head is ~320 m above the sampling point, or 60 mbgs (~280 m ASL). This is approximately the same elevation as the surface of High Lake (283.3 m ASL) and Granite Lake (278.0 m ASL), which is ~400 m north of High Lake, but significantly higher than the Kennearctic River (~200 m ASL). Both High Lake and Granite Lake potentially have taliks beneath them (Section 4.3.1), thus it is possible there is a hydraulic connection between the borehole and the taliks.

Groundwater elevations determined for HLW-05-168 (~268 to 323 m ASL) and elsewhere on the property are estimates, as both the groundwater densities and the relative mixing with drilling waters are uncertain. Densities in the boreholes could range between drill fluid (1.121 g cm^{-3}) and a completely dilute solution (1.000 g cm^{-3}), therefore estimates of groundwater elevations are only accurate within ± 55 m (Gartner Lee 2005). Further, borehole pressures were found to be decreasing with time (Gartner Lee 2006b). Generally, pressures decrease after drilling in all boreholes as drill fluids migrate into the formation. Regardless of the uncertainties associated with determining groundwater elevations at the site, results of this and the Gartner Lee studies (Gartner Lee 2005; 2006b) clearly indicate the piezometric surface at the site is well above the base of permafrost (~78 m BSL), and within 100 m of ground surface (368 m ASL). *(Note: West Zone is ~65 m higher in elevation than High Lake*).

4.3 TEMPERATURE

Temperature measurements within HLW-03-28 remained below 0 °C, indicating the borehole did not extend past the base of the permafrost as expected. The temperature sensor in the packer indicated a temperature of -0.5°C at 465 m (421 mbgs). Extrapolating thermal profiles from the Distributed Temperature Sensor (DTS) (Figure 15), the base of permafrost near HLW-03-28 is expected to be around 500m (453 mbgs), which is almost 100 m deeper than the drillers and mining company had assumed for this part of HLGB.

The DTS experiment was conducted over a span of five days, with 64 hours of heating and 58 hours of cooling (Figure 15). To interpret the acquired thermal transients, a 1-dimensional radial model explicitly incorporating the fluid-filled borehole and steel casing, surrounded by rock with homogeneous thermal properties, was used to invert cooling data. Phase changes (solid ↔ liquid) which were observed to occur were not explicitly incorporated, but will be for future analysis. Heating data is not used because small variations in spatial distance between the fiber-optic cable and the heating cable create large differences in temperatures. However, during cooling, conduction of heat tends to homogenize temperatures near the wellbore, making the simulations insensitive to the exact separation between the heating cable and monitoring fiber-optic cable.

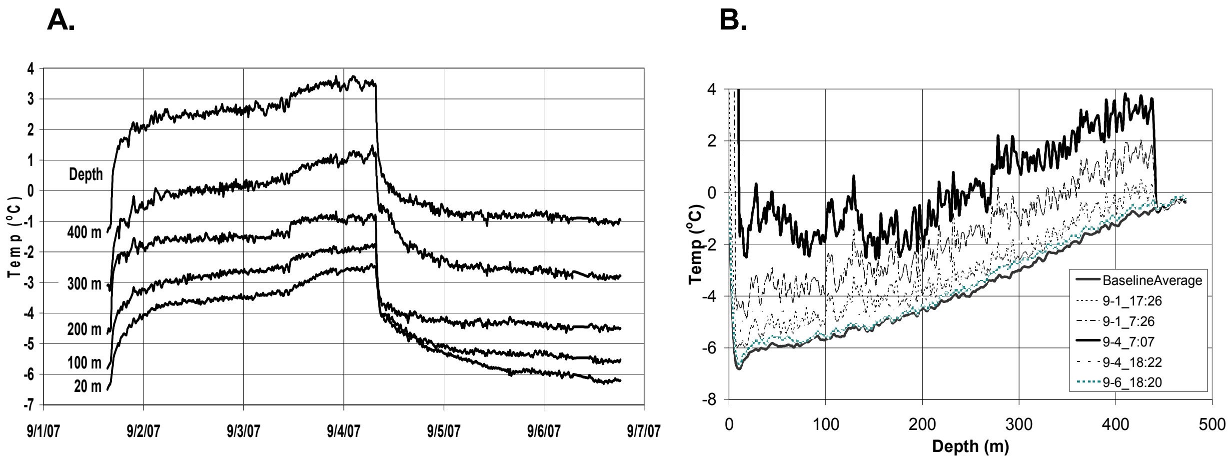


Figure 15: High Lake thermal profiles acquired using a distributed temperature sensor. Heating was initially conducted at a rate of 16.8 W m^{-1} for 43 hours followed by heating at 20.5 W m^{-1} for 21 hours. Following the geothermal gradient, the thermal profiles go from coolest (shallowest) to warmest (deepest). (A) Profiles at individual depths with time, and (B) profiles with depth plotted at specific times.

Using the 1-dimensional model to invert the DTS data, thermal conductivity is estimated along the length of the wellbore with a spatial resolution equivalent to the 1-meter resolution of the DTS (Figure 16). The results shown in Figure 16 are consistent with the known lithology, in which higher thermal conductivity mafics are overlain by lower thermal conductivity felsics. The high thermal conductivities are attributed to zones in which the core was observed to consist of ≥50% pyrite. Using the baseline temperature profile (Figure 15) and the thermal conductivity (Figure 16), the vertical heat flux can be estimated in the vicinity of the wellbore. Using averaged values for thermal conductivity, within the felsics at a depth of 50 to 100 meters, a heat flux of 32 mW/m^2 is estimated, whereas at a depth between 300 and 400 meters, the heat flux is much greater (73 mW/m^2). Without more detailed information on the 3-dimensional shape of the ore body, it is impossible to know if this difference can be attributed to lateral heat flux, or if the differences in heat flux are attributable to climate variability as is observed at other locations (Harris et al., 1997; Lachenbruch et al., 1986).

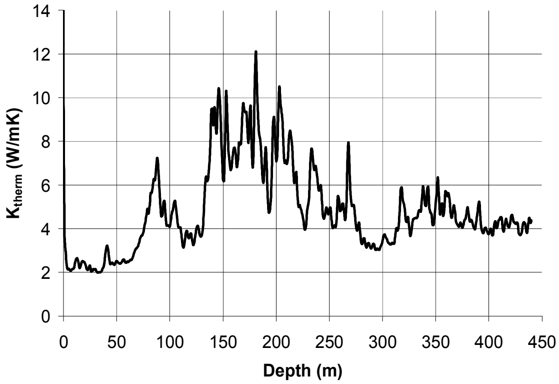


Figure 16: Thermal conductivity as a function of depth using a 1-dimensional model to invert DTS data. The results are consistent with geology, in which shallow tuffs are underlain by ore bearing mafic intrusives.

During DTS experiments, the coldest part of the borehole was -2°C; however the upper 275 m of the borehole remained below freezing for the duration of the experiments (Figure 15). The coldest sections correspond to a zone of high thermal conductivity (Figure 16) in the ore zone (150-200m), well below where the thermal minimum occurs in undisturbed conditions. A further discussion of the DTS experiments is available in Freifeld et al. (2008a,b).

4.3.1 Taliks

BGC Engineering Inc. and Gartner Lee, Ltd. conducted limited monitoring on the permafrost conditions (BGC Engineering Inc. 2005; Gartner Lee, Ltd. 2006b). There is greater variation in both topography and lithology at High Lake than at Lupin, which results in greater variation in permafrost thickness at High Lake. The base of permafrost ranges from 360 to 440 meters below ground surface, as defined by the 0°C isotherm (Gartner Lee, Ltd. 2006b). The geothermal gradient is approximately 1.6°C/100 m (Figure 17; BGC Engineering Inc. 2005).

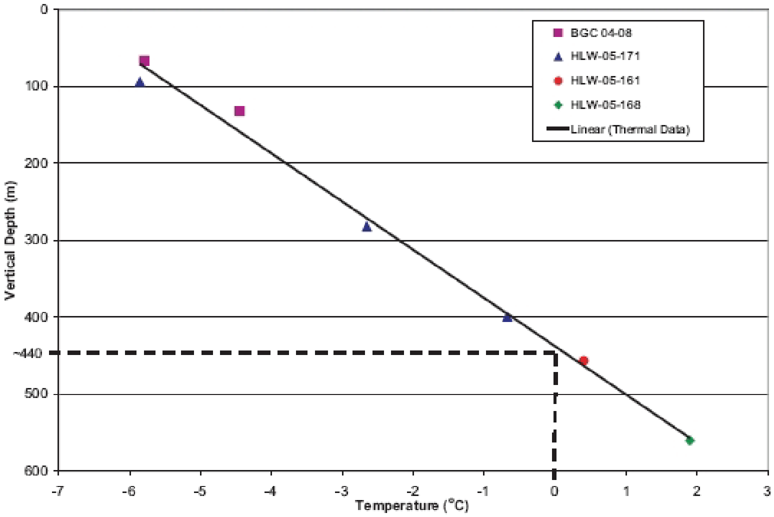


Figure 17: Temperature measurements at High Lake (from BGC Engineering Inc. 2005).

Based on temperature measurements, thermal models have been constructed for the area near High Lake (Gartner Lee 2006a). The thermal models indicate that it is likely that taliks are present beneath High Lake and sections of the Kennearctic River near HLW-03-28 (Figure 18). GPR performed at the Lupin site during Phase III of the PERMAFROST Project indicated the presence of taliks near the lakes at Lupin and could be applied to the High Lake area (Stotler et al., 2009).

As part of the environmental assessment conducted by Gartner Lee, Ltd. in 2006, three boreholes were drilled beneath High Lake and L12 in the west zone (Figure 14). BH06-T1 was drilled to a depth of 44.5 meters beneath the north end of High Lake, where a talik is believed to exist. 40 L of water was purged from a section of borehole containing 7 L of water in order to collect representative talik samples. The geochemical results will be discussed further in Section 5.

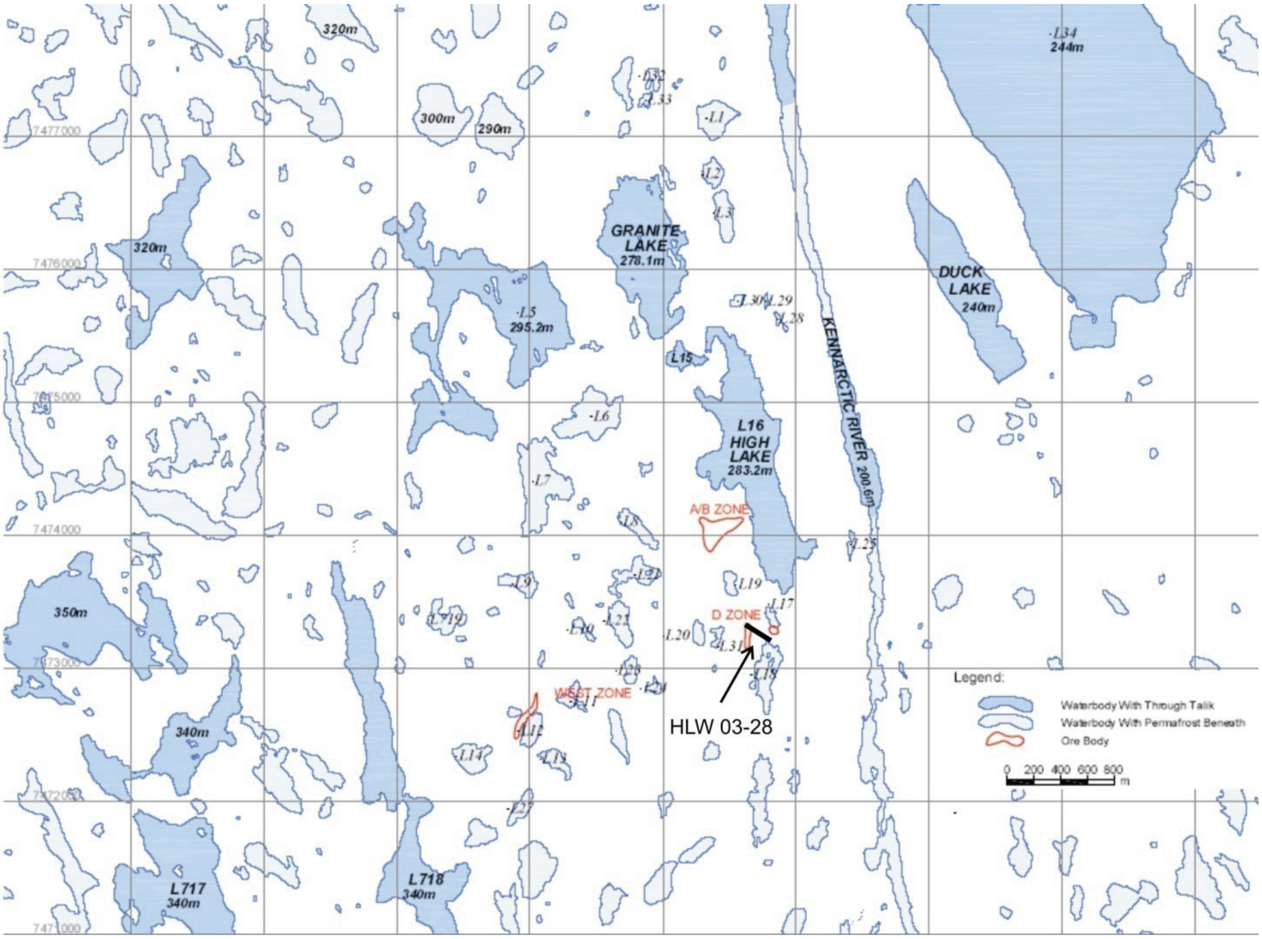


Figure 18: Map of lakes predicted by thermal models to have taliks beneath them (dark blue) and predicted to be without taliks (light blue) in the study area (Modified from Gartner Lee, Ltd. 2006a).

5. GEOCHEMISTRY

5.1 SURFACE WATER SAMPLING

Surface water samples were collected from six lakes (High Lake, L20, L21, L22, L31, and Core Shack Lake) of varying size within a 3 km radius of borehole BH06-T1, as well as Sand Lake which is ~13 km north of High Lake (Figure 12; Table 4). Core Shed Lake was also used as the source water for drilling activities.

Table 4. Summary of water chemistry and isotope results from surface water bodies.

Location	pH (lab)	Cond.(lab) mS/m	Na/Cl ratio meq/L	Ca/Na ratio meq/L	$\delta^{18}O$ ‰ VSMOW	$\delta^{2}H$ ‰ VSMOW	^{3}H TU
Core Shed Lake	6.5	4.9	0.43	5.25	-18.25	-150	11.7
Lake L20	6.7	11	0.20	6.55	-17.1	-145	12
Lake L21	6.4	2.2	0.85	3.44	-17.55	-146	12
Lake L22	6.5	3.9	0.80	3.72	-17.57	-145	10.9
Lake L31	6.8	15	0.14	11.59	-14.7	-132	11.9
High Lake	6.6	8.1	0.58	6.49	-18.3	-147	11.2
Sand Lake					-19.14	-154	9.6

A summary of lake chemistry was previously conducted by the Geological Survey of Canada (Cameron and Ballantyne 1975) and a large, multi-year survey of lake chemistry was also commissioned by Wolfden for the Environmental Assessment (Gartner Lee 2006c,d).The results of these surveys are similar to this smaller survey, showing surface waters in the area generally are low salinity, Ca-SO_4 to Ca-HCO_3 type waters. Isotopic analyses were not performed as part of the previous surveys.

5.2 TALIK WATERS

A talik water sample from 44.5 meters beneath High Lake (BH06-T1) obtained by Gartner Lee in 2006 reveals that relatively shallow talik water is chemically similar to surface water (Table 5; Gartner Lee, 2006b). The surface water sample (L16B-B) was obtained in a previous study by Gartner Lee at the same time as the talik sample. Conductivity, hardness, pH, and major ions are all slightly higher in the groundwater, while dissolved metal concentrations are generally lower in groundwater, with exceptions such as antimony and molybdenum (Table 5; Gartner Lee Ltd. 2006b). Water flow was assumed downwards from the lake, and natural processes such as adsorption, cation exchange, or precipitation may cause the decrease in metal concentrations in the groundwater (Gartner Lee, Ltd. 2006b).

Table 5. Chemical comparison of High Lake talik (BH06-T1) and surface (L16B-B) waters from Gartner Lee, Ltd. (2006b).

Parameter (mg/L)	BH06-T1	L16B-B
Depth (m below ice surface)	44.5	-
Physical Tests		
Conductivity (µS/cm)	132	102
Hardness as $CaCO_3$	53	48
pH	7.4	6.94
Dissolved Anions		
Bromide	<0.050	-
Chloride	4.9	3.64
Fluoride	0.083	-
Sulphate	33.9	26.6
Nutrients		
Nitrate Nitrogen	<0.0050	<0.0050
Nitrite Nitrogen	<0.0010	<0.0050
Dissolved Metals		
Aluminum	0.034	0.0279
Antimony	0.00116	<0.00010
Arsenic	<0.00050	0.00011
Barium	<0.020	0.00464
Beryllium	<0.0010	<0.00050
Boron	<0.10	<0.010
Cadmium	0.00054	0.00193
Calcium	13.8	9.21
Chromium	<0.0010	<0.00050
Cobalt	<0.00030	0.00359
Copper	0.0051	0.175
Iron	<0.030	<0.030
Lead	<0.00050	0.000101
Lithium	<0.0050	<0.0050
Magnesium	4.47	3.37
Manganese	0.0275	0.0504
Mercury	<0.000020	<0.000050
Molybdenum	0.0325	0.000072
Nickel	<0.0010	0.0022
Potassium	<2.0	0.673
Selenium	<0.0010	<0.0010
Silver	<0.000020	<0.000010
Sodium	3	1.77
Thallium	<0.00020	<0.00010
Tin	<0.00050	0.00159
Titanium	<0.010	<0.010
Uranium	<0.00020	<0.000010
Vanadium	<0.030	<0.0010
Zinc	0.0058	0.678

5.3 MATRIX FLUIDS

5.3.1 Crush and Leach Fluids

Eight sections of core were selected for crush and leach analysis (Table 6). Core was carefully selected throughout the length of borehole column to analyze fluids from similar rock types. Selecting similar rock types from the entire borehole column allows for the possibility to determine what, if any, affect the permafrost has on matrix fluids. Several sections were also selected from the portion of the borehole previously drilled by Wolfden Resources. This core had been stored on the surface in open core boxes shortly after drilling and logging by Wolfden was completed. Crush and leach techniques and rationale used were the same as those followed in Phase III of the PERMAFROST project (Stotler et al. 2009) and are detailed by Frape et al. (2004) and Smellie et al. (2003). Measured chemical compositions from the matrix fluids are shown in Table 7 and Table 8. Low chloride values were observed in the leach fluids from High Lake, similar to chloride values observed for matrix fluids at the Lupin site (Stotler et al., 2009).

Table 6. Summary of core properties, quantities of rock and water, and rock type used in the leaching experiments, borehole HLW-03-28.

Segment along borehole strike (m)	Depth Vertical (m)	Length of Core (cm)	Rock Mass (g)	Water Vol. (mL)
33.4-33.6	30.36	20	791.92	792
75.76-75.92	68.70	16	599.64	600
112.87-113	102.32	13	525.93	526
128.00-128.17	116.10	17	767.67	767
219.99-220.17	199.48	18	704.11	704
318.68-318.89	288.93	21	872.5	872
343.00-343.16	310.95	16	405.5	405
358.76-358.94	325.18	18	570.07	570

Table 7. Chemical composition of leach fluids (values are for solution concentration and not corrected for rock mass), borehole HLW-03-28.

Depth m	B µg/L	Li µg/L	Mn µg/L	Sr µg/L	Fe mg/L	Na mg/L	K mg/L	Ca mg/L	Mg mg/L	Br mg/L	Cl mg/L	SO_4 mg/L
30.36	266	14.8	12.8	20.3	1.25	67.4	49.7	4.31	2.09	240	30	26
68.70	154	12.1	18.1	5.22	1.19	42.1	139	1.34	1.75	240	21	15
102.32	310	46.9	1.94	41.3	<0.03	58.9	115	26.4	12.8	299	38	123
116.10	326	11.8	3.14	34.7	<0.03	30.5	125	26.0	6.69	245	32	131
199.48	40.1	0.70	0.78	39.3	<0.03	16.9	19.1	5.95	21.2	70.3	7.1	2.6
288.93	171	17.8	71.9	888	<0.03	38.3	34.8	724	50.8	288	25	2000
310.95	95.8	0.45	0.88	8.93	0.08	33.1	57.3	2.57	2.66	162	13	8.4
325.18	248	1.43	15.9	5.94	0.86	37.1	102	1.67	0.84	190	11	4.8

Table 8. Calculated concentrations of major ions in mg/kg rock (ppm), corrected for weight of solid leached and weight of leachate used (water: solid ratio was 1:1), borehole HLW-03-28.

Depth m	B mg/kg	Li mg/kg	Mn mg/kg	Sr mg/kg	Fe mg/kg	Na mg/kg	K mg/kg	Ca mg/kg	Mg mg/kg	Br mg/kg	Cl mg/kg	SO$_4$ mg/kg	δ^{37}Cl ‰SMOC
30.36	0.27	0.0148	0.0128	0.02	1.25	67.4	49.7	4.31	2.09	0.24	29.60	26.3	0.4
68.70	0.15	0.0121	0.0181	0.01	1.19	42.1	139	1.34	1.75	0.24	20.91	14.7	-0.3
102.32	0.31	0.0469	0.0019	0.04	<0.03	58.9	115	26.4	12.8	0.30	37.50	123	1.2
116.10	0.33	0.0118	0.0031	0.03	<0.03	30.5	125	26.0	6.68	0.24	32.17	131	-0.2
199.48	0.04	0.0007	0.0008	0.04	<0.03	16.9	19.1	5.95	21.2	0.07	7.10	2.60	0.1
288.93	0.17	0.0178	0.0719	0.89	<0.03	38.3	34.8	724	50.8	0.29	24.59	1999	0.4
310.95	0.10	0.0004	0.0009	0.01	0.08	33.1	57.2	2.57	2.66	0.16	13.38	8.39	0.9
325.18	0.25	0.0014	0.0159	0.01	0.86	37.1	102	1.67	0.84	0.19	11.40	4.80	-0.2

The crush and leach technique is a classic method for determining concentrations of conservative ions (Cl, Br) in pore water (Waber and Frape, 2002; Smellie et al., 2003; Gaucher et al., 2006). Crush and leach is often also used to obtain information about concentrations of other ions (eg.cations) which may not be conservative. Concentrations of non-conservative species determined using crush and leach can be influenced by the dissolution of minerals, or oxidation of the rock sample, during the experimental procedure. In this case, the measured compositions by crush and leach may not be representative of the composition of the pore water. As described by Gaucher et al. (2006), a plot of ion concentration as a function on the solid/liquid ratio of the batch system can be useful to determine whether an ion has behaved conservatively during the crush and leach process. If the species is conservative, data will plot as a straight line, while a hyperbole indicates data is impacted by mineral dissolution, and scattered data suggests oxidation of the rock sample has impacted the results (Gaucher et al., 2006). However, concentrations of conservative ions Cl and Br obtained by crush and leach in this study are likely representative of pore water compositions. Bromide concentrations are unchanged with depth down the column. Chloride concentrations shows slightly more variability than Br, with a trend of decreasing concentrations from 288.9 m to 325.2 m which is also observed in Ca, Mg and SO$_4$ crush and leach results. While interpreting the results for SO$_4$ and the cations (Ca, Na, K, Mg), it must be considered that the impact of mineral dissolution and/or sample oxidation during leaching has not been determined for these samples, therefore the relationship between the crush and leach data and actual pore water compositions is not precisely known. However, it can be observed that with depth along the borehole, calcium, magnesium, and sulphate concentrations show the greatest variation (Figure 19). Near the bottom of the sampled portion, both SO$_4$ and Ca spike, just before Ca, Mg, SO$_4$, and Cl concentrations decrease. Sodium concentrations generally decreased with depth down the column. The spikes in Ca and SO$_4$ concentrations occur near the felsic volcanics sections of the borehole, and if the crush and leach data is representative of the pore water compositions, this may suggest that rock chemical history has had a stronger influence on overall matrix chemistry along this borehole than the freezing process. Additional crush and leach samples are currently being prepared to study deeper sections of the borehole.

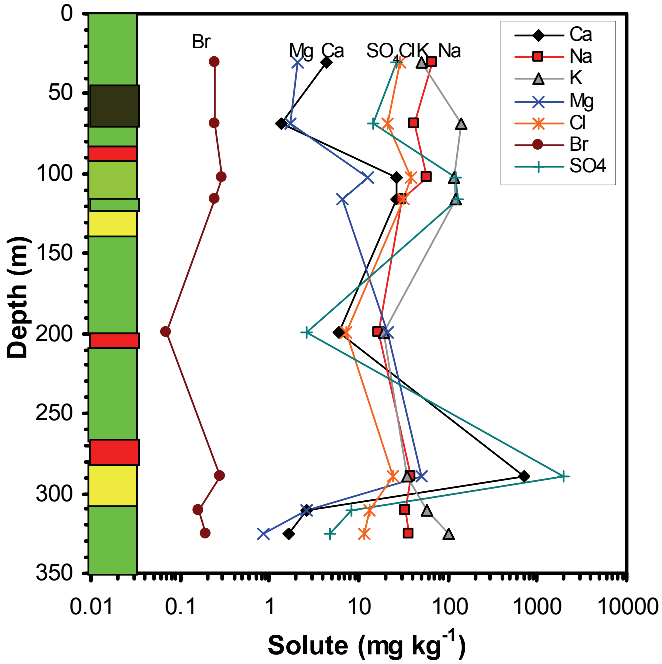


Figure 19: Profiles of calculated concentrations of ions in rock (crush and leach experiments) along the borehole in HLW-03-28. The borehole log (along y-axis) is generalized from Figure 10 (the same color scheme is used here: flourescent green is intermediate volcanic rock, dark green is a diabase dyke, olive green is mafic volcanic rock, red is the mineralized zone, and yellow is felsic volcanic rock).

There is significant (1.5‰), and apparently unsystematic, variation of δ^{37}Cl values in matrix fluids obtained by crush and leach with depth along the borehole (Figure 20). Variations in δ^{37}Cl values have been previously observed within different sedimentary and crystalline units of the Williston Basin formation (Shouakar-Stash, 2008). In addition, Lambie (2008) found that heterogeneity in δ^{37}Cl values within cores obtained from AECL's Underground Research Laboratory (URL) may be due to water-rock interactions. Assuming that the variations in δ^{37}Cl values observed at High Lake are due to similar processes as those identified in the Williston Basin and at the URL, the variations in δ^{37}Cl values observed at High Lake may potentially be attributed to changes in geologic setting with depth through the borehole.

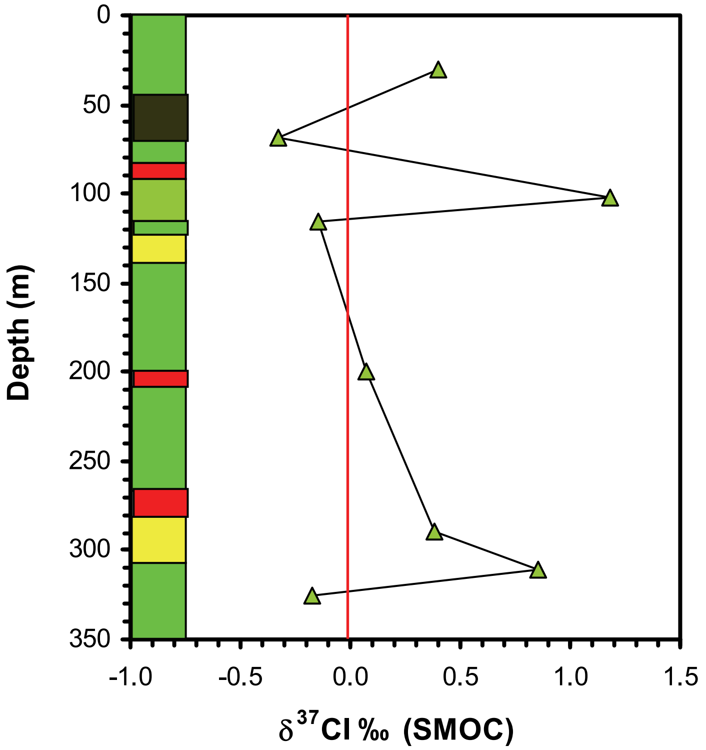


Figure 20: Profile of δ^{37}Cl along the borehole length from crush and leach experiments in HLW-03-28. Rock types in the borehole log (along y-axis) are represented by the same color scheme as Figure 10 and Figure 19.

5.4 BOREHOLE WATERS: BAILED WATERS AND U-TUBE SAMPLES

In 2006, the borehole froze (Section 3.1) before samples could be collected with more precise sampling techniques, therefore bailed waters were the only borehole waters available for chemical and isotopic analysis (Table 9). Because significant quantities of water were removed from the borehole with each bail (Section 3.1), it was thought that the sampled waters would be representative of relatively uncontaminated formation waters.

Table 9. Chemical and isotopic analysis of bailed waters and drilling salt.

Bailed Waters	B μg/L	Li μg/L	Mn mg/L	Sr mg/L	Fe mg/L	Na meq/L	K mg/L	Ca mg/L	Mg mg/L	Cl mg/L	$\delta^{18}O$ ‰ VSMOW	$\delta^{2}H$ ‰ VSMOW
HLW0328-1							29.8	37500	41.2	69500	-17.74	-147.43
HLW0328-4							29.2	9810	36.1	19400	-22.17	-175.31
HLW0328-6							26.5	7210	32.7	14300	-22.51	-177.22
HLW0328-7							25.8	7540	31.0	13100	-22.59	-177.41
Salt	<100	<100	0.53	124	<2	6.217391	33.3	241000	156	374000		

In 2007, the U-tube was purged 7 times during the field excursion with water collection for chemical analysis occurring during purges 1, 4, 6, and 7. Table 10 contains the dates and volumes collected for all the purges. All water chemistry samples were filtered through a 0.2 μm syringe filter. Gas samples were taken during purges 4 and 6 using gas collection cylinders. Sampling ended after 7 purges when the sample lines froze. The total amount of water contained in the borehole beneath the packer assembly is estimated to be 518 L.

Table 10. Volume of water collected from the deep borehole assembly and the date at which it was extracted.

Purge #	Volume Collected (L)	pH	Eh	EC	Date/Time Collected
1	13.60	5.43	-115	>20 mS	July 30, 2007 11:40
2	7.96	6.50	-133	13.2 mS	July 30, 2007 19:42
3	10.57	8.56	-150	>20 mS	July 31, 2007 13:52
4	9.63	6.69	-111	>20 mS	August 1, 2007 10:41
5	6.81	7.76	-150	4% wt salt*	August 1, 2007 21:15
6	6.27	7.25	-177	4% wt. salt*	August 2, 2007 11:00
7	7.84	8.50	-180	4.1% wt salt*	August 2, 2007 21:25
8	2.28	9.15	-69	4.1% wt salt*	August 3, 2007, 9:50
TOTAL PURGED	**62.68**				

*Refractometer used to measure EC.

There are several indications suggesting water from U-tube purges 4, 6, and 7 represent mixtures of drill water with 50% or more natural water, with purges 6 and 7 containing the highest percentage of natural water (Table 11). Uranine concentrations in drill fluids were diluted during drilling due to melting of borehole ice, thus additional uranine was added to drill fluid before the final drill fluid sample was collected, just before the borehole ice completely melted. Given the additional inputs of uranine into the drill fluid, the initial concentration of uranine added to the borehole before purging cannot be accurately determined. The observed uranine dilution in the first purge sample suggests drill fluid mixed with fluid already in the borehole (Table 11). Tritium activity in the purged samples also suggests mixing of drill water with natural water, and predicts a slightly larger component of surface drill fluids in the purged samples compared to the estimate derived using uranine concentrations (Table 11). Tritium is sensitive to all drill fluids introduced to the borehole, including those from 2006 when the borehole was extended. Therefore, tritium provides information about the total amount of fluid added to the borehole, while uranine provides information about the amount of drill fluid added during this year’s work only. While the collection of additional samples would be useful, the information obtained from the existing samples gives an estimate of the relative contribution of drill fluid in the collected samples (37% – 100%; Table 11).

Table 11. Uranine concentrations and tritium activity from drill and U-tube samples.

Sample	Date	Time	Uranine		Tritium	
			(µg/L)	% Drill Fluid*	(TU)	% Drill Fluid**
HL DW	25/07/2007	3:28	27300		NA	
HL DW	27/07/2007	-	10200		NA	
HL DW	29/07/2007	2:10	3500		NA	
HL DW	29/07/2007	7:30	10100		10.9-11.7***	
Purge 1 (HL-GTK-29)	30/07/2007	11:40	3700	36-100%	11.9	100%
Purge 4 (HL-GTK-30)	01/08/2007	10:41	1400	14-38%	5.8	49%
Purge 6 (HL-GTK-31)	02/08/2007	11:00	710	7-19%	4.4	37%
Purge 7 (HL-GTK-32)	03/08/2007	9:50	880	9-24%	4.8	40%

* The low value represents % drill fluid, calculated from the final drill fluid sample, the higher value is the % drill fluid as calculated from the first purged sample, and is considered an upper limit.

** Tritium values are typically ± 0.6. Thus, % drill fluid calculations are within ± 7%. Decay of tritium from fluids added in 2006 is not considered. % drill fluid are based on drill water tritium value of 11.7 TU.

*** Tritium was measured in two separate Core Shack Lake samples, the source for drill water, not the circulating return water.

5.5 DISCUSSION OF FLUID CHEMISTRY AND COMPARISON WITH LUPIN

Stable isotopic values of samples from the High Lake site plot near the global meteoric waterline (Figure 21). Stable isotopic values of the bailed waters are similar to drill waters and surface waters, suggesting the bailed waters may have been contaminated during drilling. This is further suggested by chlorine isotopic data (discussed later in the section). Comparing stable isotopic values of the bailed waters at High Lake with Lupin waters (Stotler et al., 2009), bailed waters are similar to waters from the 550-112 borehole at Lupin which were collected at a similar location near the base of the permafrost. However, it is most likely that the relationship of HLW-03-28 bailed waters to the drilling water is more significant, given the likelihood of contamination of the bailed waters and that the 550-112 borehole may have been impacted by drilling water.

The first U-tube sample ("1" in Figure 21A) has a stable isotopic composition similar to surface waters in the High Lake area, but samples collected during subsequent purges are similar to compositions sampled in the subpermafrost and the final 570-105 sample at Lupin (Figure 21). This shift in isotopic compositions with successive U-tube purges and correlation with Lupin samples is additional evidence suggesting that the later U-tube samples are becoming more representative of natural fluid with lesser contamination by drill fluid (37% to 49% drill fluid; Table 11). However, after sampling only two sites, it is not possible to determine whether the isotopic compositions are a result of permafrost formation, mixing of waters, or a combination of different processes.

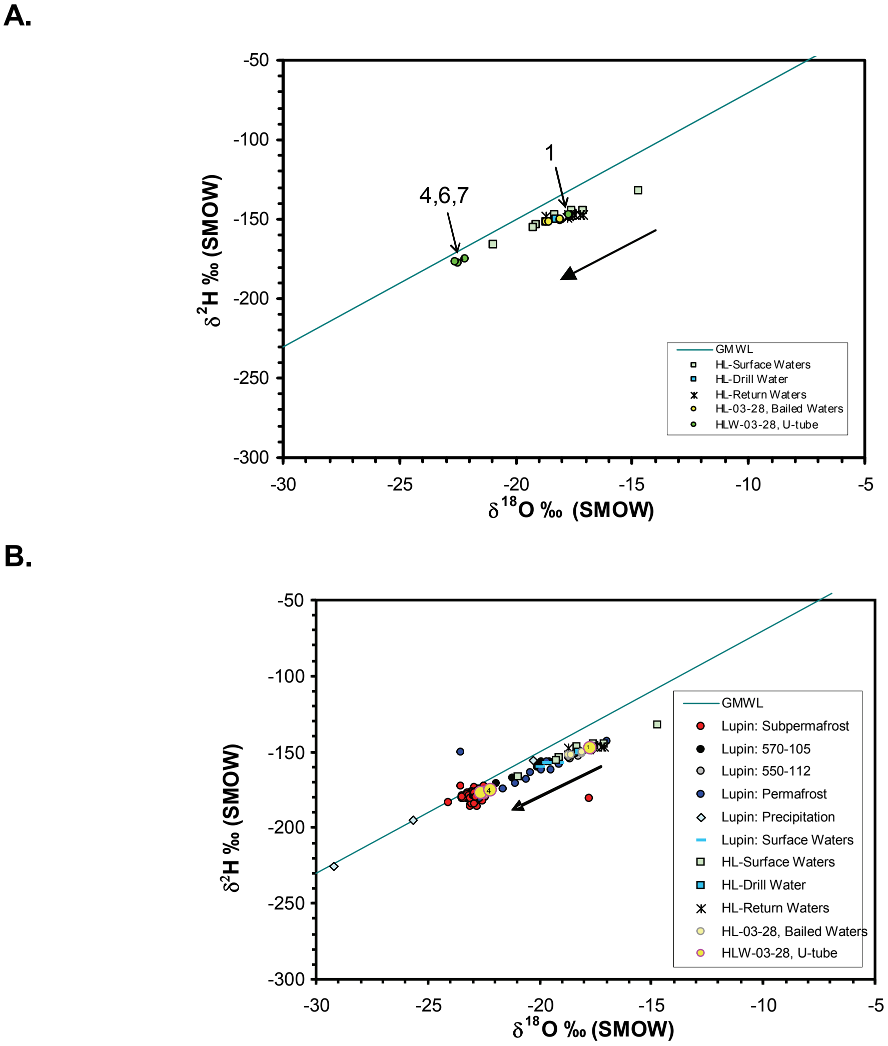


Figure 21: Stable isotopic composition of High Lake waters (A) and compared with Lupin waters (Stotler et al., 2009) (B). The first U-tube sample (1) has a similar isotopic composition as High Lake surface waters and the bailed waters, however purge samples 4, 6, and 7 have a similar isotopic composition as Lupin subpermafrost and the final 570-105 samples. Arrows indicate the direction of successive U-tube sampling.

Table 12. High Lake isotopic data plotted in Figure 21A

Location	$\delta^{18}O$ ‰ VSMOW	$\delta^{2}H$ ‰ VSMOW
HLW0328-1	-17.74	-147.43
HLW0328-4	-22.17	-175.31
HLW0328-6	-22.51	-177.22
HLW0328-7	-22.59	-177.41
HL-GTK2	-17.2	-147
HL-GTK5	-17.7	-147
HL-GTK7	-17.8	-149
HL-GTK8	-17.6	-147
HL-GTK11	-17.5	-147
HL-GTK13	-17.7	-148
HL-GTK14	-17.1	-147
HL-GTK18	-18.7	-148
HL-GTK1	-18.25	-150
HL-GTK23	-17.1	-145
HL-GTK24	-17.55	-146
HL-GTK25	-17.57	-145
HL-GTK26	-14.7	-132
HL-GTK27	-18.3	-147
Sand Lake	-19.14	-154
Kennarctic R	-19.26	-155.51
HLC-Cshack	-18.69	-151.77
HLC-Slake	-20.95	-166.13

The Na-Ca plot (Figure 22A) shows High Lake surface and shallow talik waters have similar Na:Ca compositions (Table 4, Table 9). Bailed waters plot along a probable mixing line between the surface waters and the drill salt used at High Lake, however one crush and leach sample also plots amongst the bailed water. With the exception of the one Ca-dominant crush and leach sample, matrix fluids as determined by crush and leach are generally sodium dominant and both High Lake and Lupin (Stotler et al., 2009) matrix waters have similar compositions (Figure 22B), but waters from the permafrost and basal permafrost at Lupin are quite different from the similar depth at High Lake. It should be noted that for drilling Na-salt was used at Lupin while at High Lake Ca-salt was used.

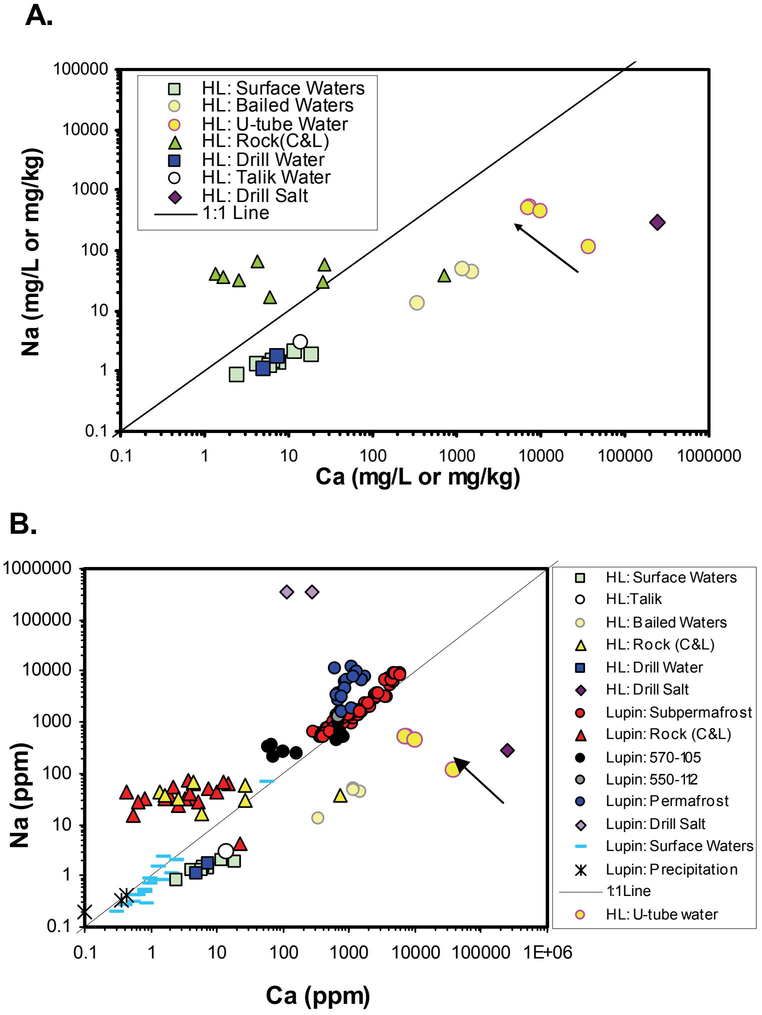
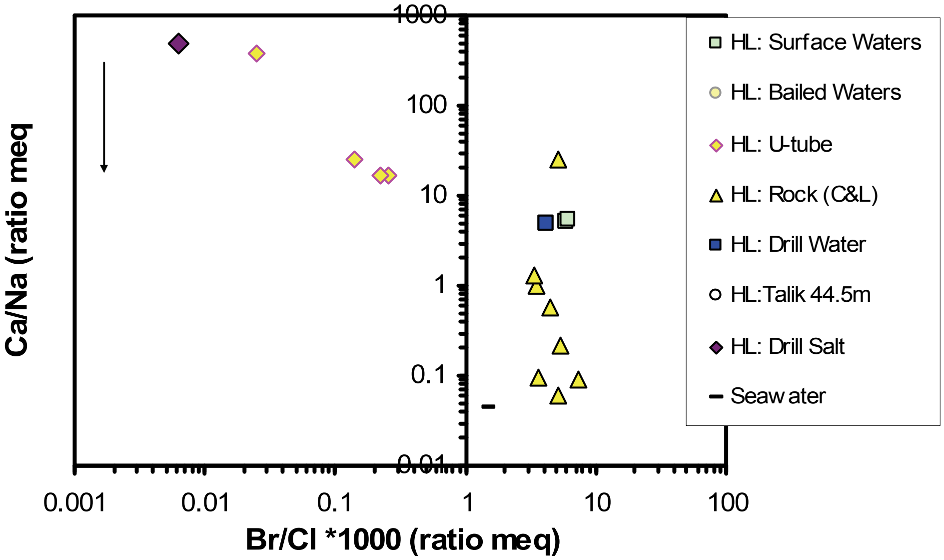


Figure 22: Sodium vs. calcium plot for (A) High Lake water samples and (B) comparing High Lake with Lupin (Stotler et al., 2009) water samples. The arrow shows the direction of successive samplings in the U-tube sampler.

Due to the low Br^- content in High Lake waters, ion ratio plots (Figure 23) are very similar to the Na vs. Ca plots (Figure 22), and also suggest bailed waters are impacted by drill salt, and have had very little influence from matrix fluids. Crush and leach determination of matrix fluids at High Lake plot in a similar area as those sampled at Lupin (Stotler et al., 2009).

A.



B.

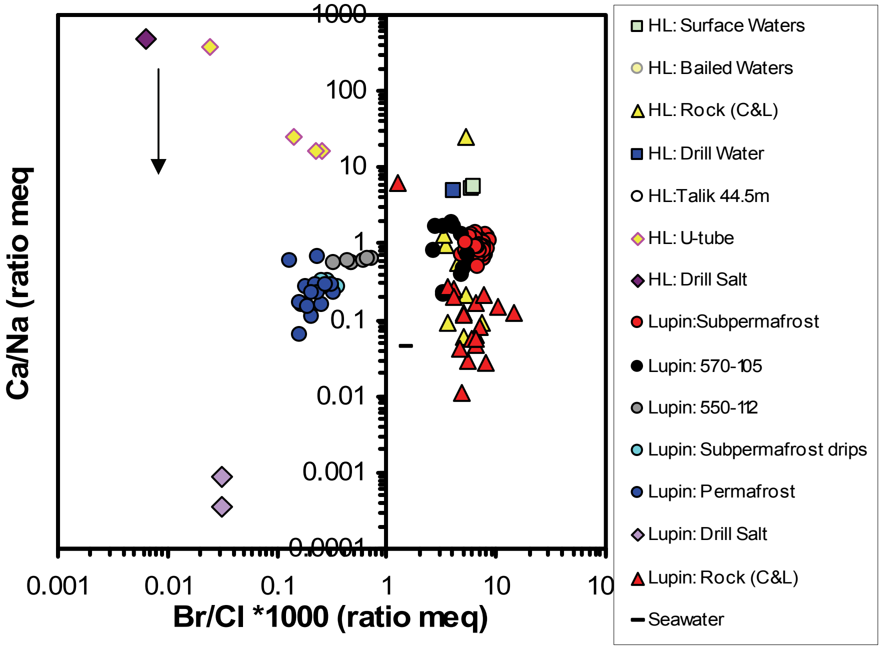


Figure 23: Ion plot for (A) High Lake waters and (B) comparing High Lake with Lupin (Stotler et al., 2009) samples. The arrow shows the direction of successive samplings in the U-tube sampler.

Chlorine stable isotopic values are plotted in Figure 24, Figure 25, and Figure 26. These plots show the bailed waters plotting more closely to the drill salt values, suggesting the bailed waters may be impacted by drill salt. The influence of drill salt on the bailed waters was also observed in Figures 21 -23 above. These observations initially seem counter-intuitive, as the borehole extension was drilled in 2006 without drill salt. However, the ice from the old portion of the borehole was melted with a combination of heat and salt prior to the research team's arrival (Section 3.1). It is suspected some of the drill brine fluid was pushed into fractures in the permafrost prior to and during drilling, and may have seeped through poorly sealed casing joints and along the outside of the casing before the casing froze. Drilling of the borehole extension may have released this chloride, which is potentially the source of chloride in the bailed water samples. Analysis of PFT in the bailed waters may provide a quantitative estimate of the extent of drill salt contamination in the samples.

Based on the results of the chemistry of the purged U-tube waters from 2007 (Table 13), purge 1 contains a high amount of calcium which likely reflects the presence of the Ca-salt drilling fluid used at High Lake. By purge 7, a decrease in the amount of calcium in the sample is observed, but a continuing rise in the sodium levels is seen with successive purges. Crush and leach samples also show high sodium levels (Figure 22a), suggesting the increase in Na in U-tube waters with successive purges may be due to water-rock interactions. Alternatively, given the high chloride levels in the purge samples, it is possible that the Na and Cl concentrations may reflect brine from drilling operations during the expansion of the borehole. This is consistent with the uranine and tritium analysis of U-tube waters, which estimate that 37% to 100% of the U-Tube water is drill fluid contamination (Table 11).

Table 13. Chemical Composition of U-tube Waters

Purge #	Br mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L
1	3.8	37500.0	41.2	111.0	29.8	69500.0
4	6.1	9810.0	36.1	451.0	29.2	19400.0
6	7.2	7210.0	32.7	496.0	26.8	14300.0
7	7.5	7540.0	31.0	531.0	25.8	13100.0

Chlorine stable isotopic compositions of matrix fluids obtained using crush and leach from High Lake have a much larger range, and are generally more enriched than Lupin matrix fluids or Canadian Shield brines (i.e Frape et al. 2003, Stotler et al. 2009) (Figures 24 -26). The process causing the isotopic enrichment and larger range of δ^{37}Cl at High Lake is currently unknown.

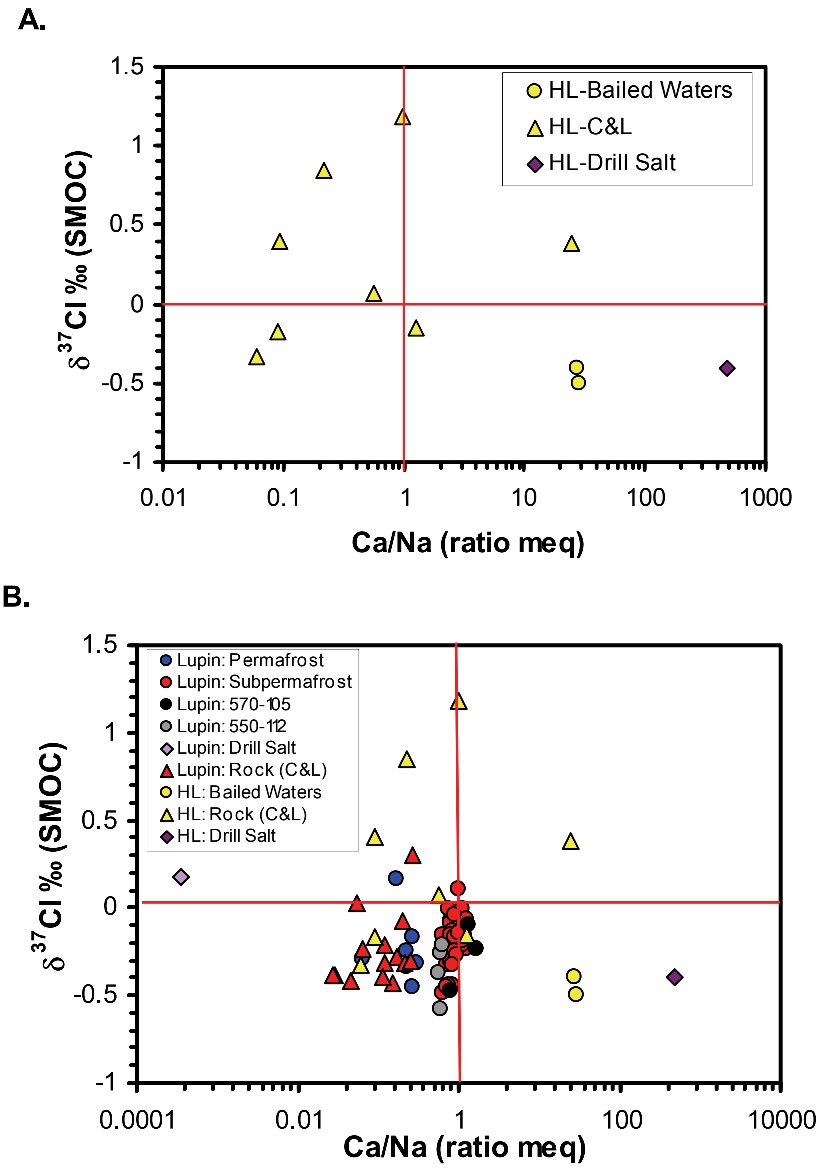


Figure 24: Chlorine stable isotopic composition versus Ca/Na ratios of High Lake samples (A) and compared with Lupin samples (Stotler et al., 2009) (B).

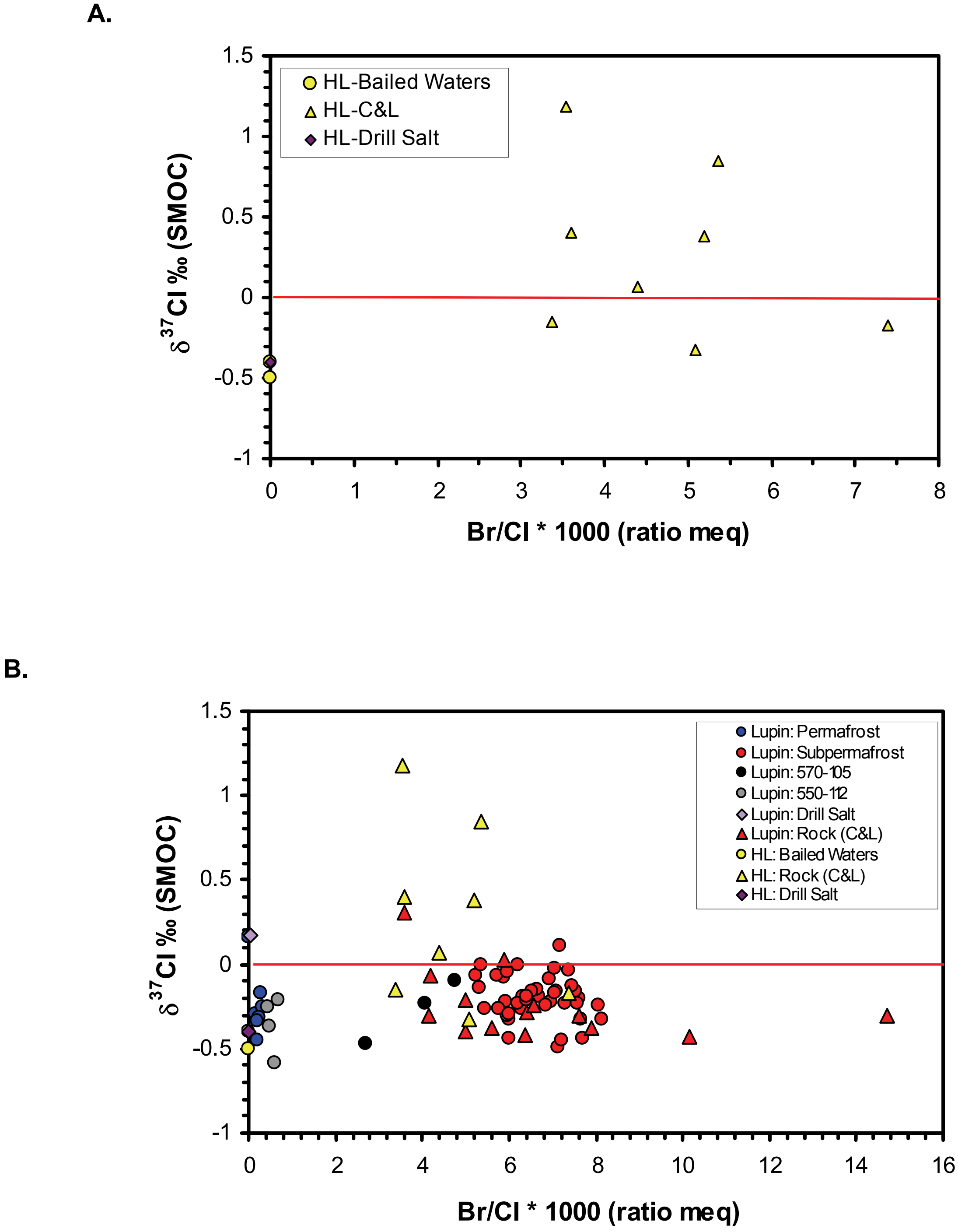


Figure 25: Chlorine stable isotopic composition versus Br/Cl ratios of High Lake samples (A) and compared with Lupin samples (Stotler et al., 2009) (B).

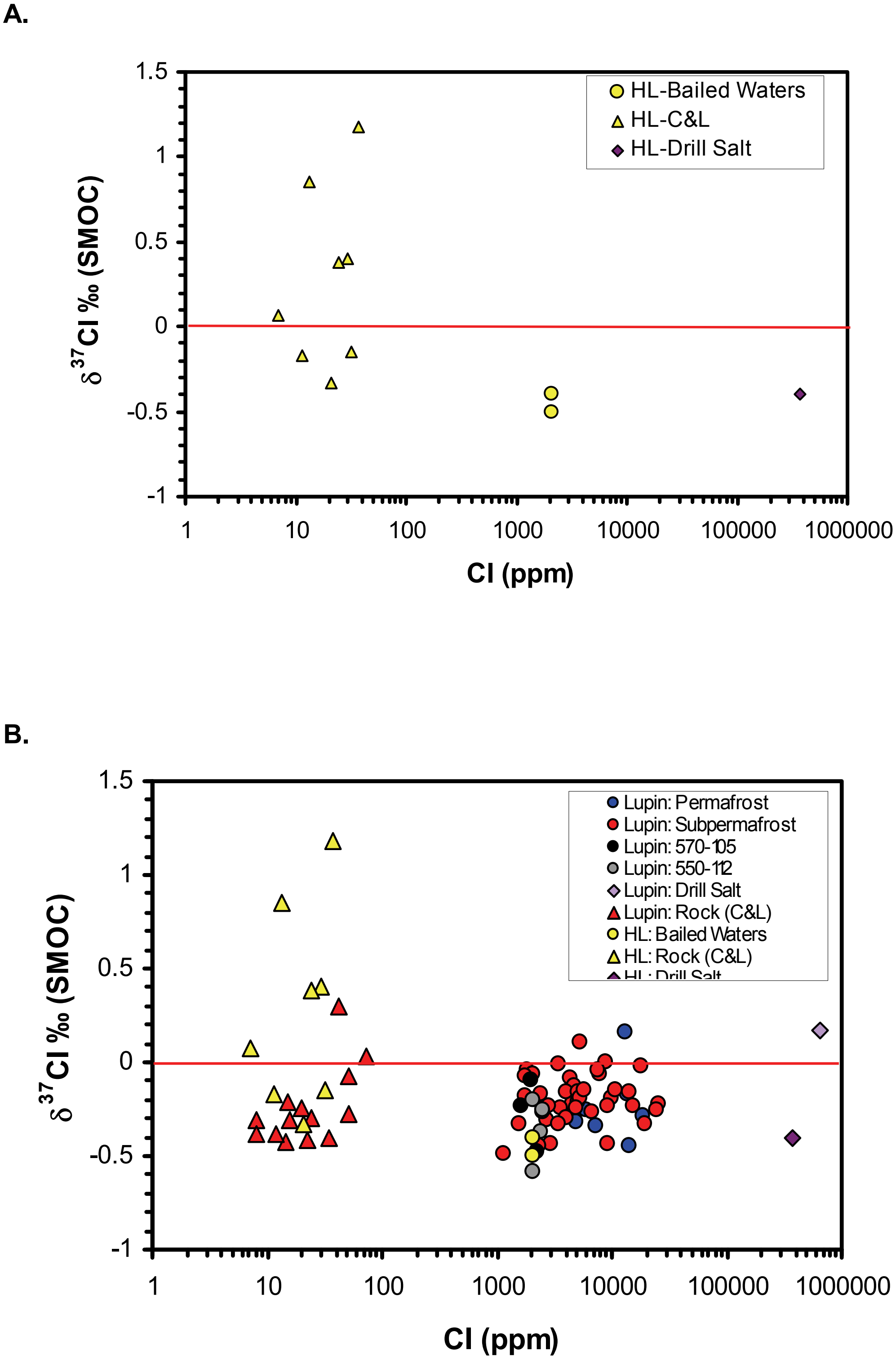


Figure 26: Chlorine stable isotopic composition versus chloride concentration of High Lake samples (A) and compared with Lupin samples (Stotler et al., 2009) (B).

5.6 GAS

Trace amounts of gas were found in the two U-tube gas samples that were collected (Table 14). At the time of analysis, the sample from Purge #6 was not under pressure and was leaking, as evidenced by the presence of oxygen in this sample. Leaking could have been a result of damage occurring during transport of the samples to the laboratory. The large amount of nitrogen in both samples is likely due to the use of nitrogen during sample collection to force the sample from the deep borehole assembly up the sample line to the surface for collection. Isotope compositions of the gas were unable to be determined due to the low quantity of gas collected, however information regarding the source of the gases can be obtained through the analysis of concentration ratios of the gases. The ratio of methane to ethane and propane (C1/(C2+C3)) in both samples (46 in purge #4, 56 in purge #6; Table 14) is not typical for bacteriogenic methane (eg. Sherwood Lollar et al.,1993c). However, the subsurface temperature and pressure conditions at the sample depth are likely within the methane hydrate stability field. If gas concentrations are sufficiently high for methane hydrate formation deeper in the subsurface, there is a possibility that the measured gas ratios (C1/(C2+C3) have fractionated by this process, impacting our ability to gain definitive information regarding the source of the gases using the gas ratio (i.e. Milkov et al. 2004, Milkov et al. 2005). However, from the data collected in this study, it is not possible to confirm whether this process (methane hydrate formation) occurred.

Table 14. Gas composition from HLW-03-28.

Parameter	**HLW-03-28, Purge #4**	**HLW-03-28, Purge #6**
% Oxygen	0.60	6.65-12.81
% Nitrogen	93	84
% Carbon Dioxide	0.05	0.06
% Methane	0.0729	0.35
% Ethene	0.0001	0.0002
% Ethane	0.0014	0.0062
% Propene	0.0001	0.0001
% Propane	0.0002	0.0001
% Butene	ND	0.0001
% iso-Butane	0.0001	0.0001
% Butane	0.0001	0.0002
Total %	**93.18**	**91.65**
C1/(C2+C3)	46	56

6. FRACTURE CALCITE

Mineral-filled fractures and veins were numerous along the cored interval of HLW-03-28. Samples were collected along the section cored in August 2007 for $\delta^{13}C$ and $\delta^{18}O$ isotopic and micro-thermometric analyses. At the time of this report, thin sections have been prepared, however micro-thermometric analysis of the samples has not been completed.

Fracture calcite stable isotopic values show very little variation in HLW-03-28 (Table 15; Figure 27). Comparing the isotopic results of calcite at High Lake with results from other sites within the Slave province, (ex. Shelton et al., 2004) shows that High Lake calcites are isotopically similar to calcite in other greenstone belts. Results from Lupin (Stotler et al., 2008) are anomalous in that the range of isotopic values measured in calcites is much larger than the range observed in other greenstone belts, including at High Lake (Figure 29B).

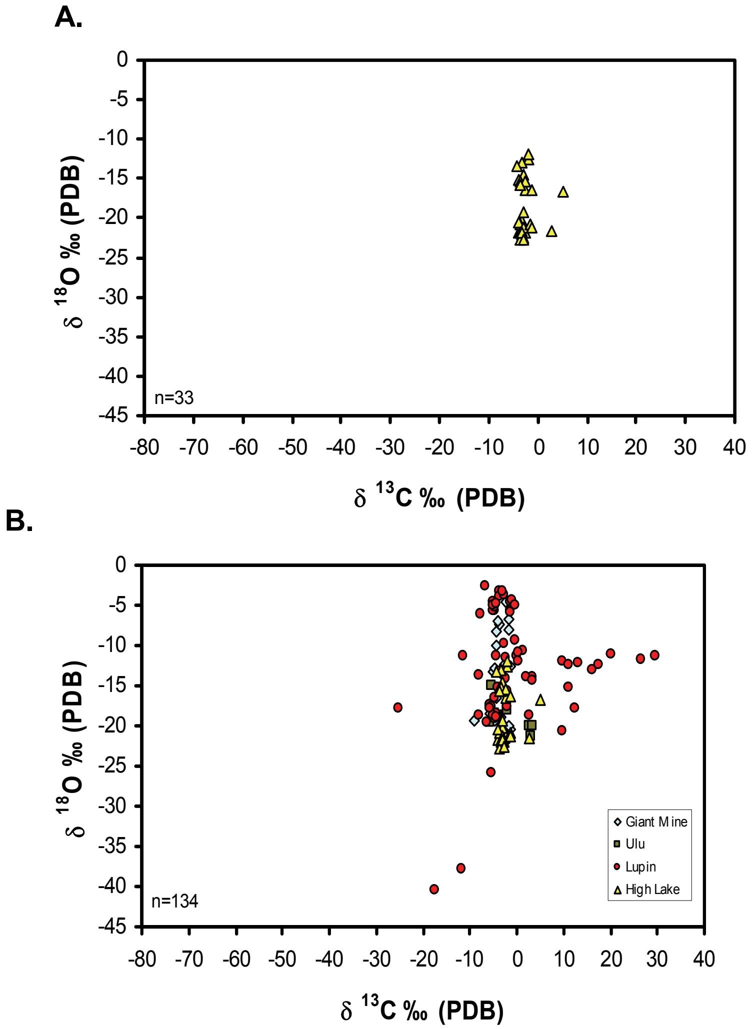


Figure 27: (A) High Lake fracture calcite isotopic results. (B) Summary of available Slave Province fracture filling calcite isotopic values with data from: Stotler et al. 2009 (Lupin), Kleespies, 1994 (Ulu) and Shelton et al. 2004 (Giant Mine).

Table 15. Fracture Calcites Sample Results from HLW-03-28.

Depth (m)	$\delta^{13}C$ PDB	$\delta^{18}O$ PDB
338.9	-3.7	-21.3
339.8	-2.5	-13.6
343.0	-3.3	-22.1
346.6	-2.1	-12.0
360.3	-2.5	-21.3
366.9	-2.5	-15.4
368.3	2.8	-21.6
378.7	-2.5	-16.5
387.8	-3.5	-15.7
393.7	-3.2	-20.3
400.0	-3.0	-19.3
402.2	-3.3	-21.7
406.5	-3.0	-21.2
416.4	-3.5	-15.3
429.3	-4.2	-13.3
430.3	-3.6	-16.7
430.5	-3.6	-18.8
430.5	-3.8	-15.1
433.2	-3.1	-22.6
436.7	-3.6	-22.2
436.7	-3.2	-17.0
440.5	-3.9	-21.8
451.2	-3.3	-21.3
465.0	-4.0	-20.5
476.9	-3.3	-13.1
496.9	-2.2	-21.0
498.7	-3.6	-22.8
508.7	-2.8	-22.6
522.3	5.0	-16.7
526.3	-1.3	-16.4
528.7	-1.5	-20.9
531.6	-1.3	-21.3
436.7	-3.2	-21.8

7. SUMMARY

In Phase IV, the PERMAFROST Project attempted to sample natural subpermafrost waters from surface at an undisturbed site. Both advantages and disadvantages to this approach were realized compared with the underground investigations conducted in Phases I-III. The underground approach is able to provide high quality groundwater samples below 800 m, but investigations of gases at these depths are susceptible to depressurization due to mine drawdown, which also affects estimates of freshwater head. On the other hand, the surface approach utilizing a DBA, applied in Phase IV of the project, provided high quality physical information, and while significant contamination of the samples (37% to 100% drill fluid) occurred, results from chemical analysis of the samples from near the base of the permafrost were able to provide some useful information. While significant drill fluid contamination was observed in the samples collected by bailing of the borehole and purging of the U-tube, this study indicates that if the problem of sample line freezing is overcome, , the DBA approach has the potential to provide high quality chemical samples.

With the experience gained from this Phase, future investigations of the basal permafrost and subpermafrost environment should consider the following:

1. Drilling:
    a. If drilling is to be successful with dilute heated water, drilling should proceed at a much slower rate than typical, to heat the rock surrounding the borehole. An adequate amount of time and funding must be allotted in initial planning to allow for extended drilling operations or complications that may arise during drilling. This will allow a maximum of 24 hours for installation of a DBA.
    b. Heated dilute drill water should have a target temperature of 60°C. Waters near boiling (i.e. 90°C) may in fact freeze more quickly than cooler waters (40-60°C). This effect is known as the Mpemba Effect, in which hot water freezes faster than cold water, under certain conditions such as when ambient temperatures range from -5 to -11°C (Jeng, M. 2006). Knowledge of the Mpemba Effect may be helpful in the continuous extraction of water from the site through the DBA.
    c. If the drill string has to be removed at any point prior to completion of the hole (e.g. for bit change), it is likely that the loss in momentum will cause freezing in the borehole, and the drill string may freeze in the hole. The dilute drill water will then have to be replaced with brine, but once downward progress has been resumed, can be diluted again. If the drilled borehole is productive, and the technical instrumentation allows flushing or pumping through the permafrost, contamination with drilling brine can be overcome. Drilling brine contamination will be a less severe problem at sites where the minimum rock temperatures are higher than at High Lake (min. -7°C).
    d. If drilling is done in frozen bedrock with highly fractured zones, casing should be considered to allow later access to the hole as circulation of hot water may enhance caving and plugging of the hole.
    e. When drilling a hole for research such as this, it is important that: 1) the depth of permafrost at the drilling site be known as precisely as possible and 2) the borehole instrumentation must be on-site and ready for immediate installation once drilling is complete.
    f. Any downhole soundings or testings, e.g. to locate flow points, are hazardous due to the freezing risk and should be avoided if possible.

2. Borehole Planning (extending a borehole vs. drilling a new borehole from surface):
    a. Drill brine contamination was evident in the subpermafrost samples (37% to 100% drill brine contamination; Table 11), even when dilute water had been used for drilling. Based on chemical and isotopic data, this brine contamination was likely due to remnant drilling brines from previous workings in the borehole. The low salinity of the subpermafrost fluids may have contributed to the significant impact of drill brine in the samples.
    b. At exploration camps, most boreholes will be drilled through or towards metallic ore zones with high thermal conductivities. If these zones are within the

permafrost, water sample recovery will be difficult due to low ambient temperatures within the borehole.

3. Deep Borehole Assembly:
    a. The sampling lines and heat tape should be wrapped in insulation to help prevent freezing.
    b. To further prevent freezing, a secondary heat tape should be considered during installation.
    c. The deployed heat tape should have a larger heat capacity.
    d. Given the likelihood that it may not be possible to retrieve samples from the surface again, the pressure sensor needs to be able to measure electrical conductivity as well as pressure and temperature.

Surface and shallow talik waters in the High Lake area are dilute. Results from crush and leach experiments suggest that matrix fluids from HLW-03-28 are also very dilute, similar to those sampled at Lupin. Chemical and isotopic analyses indicate that waters bailed from HLW-03-28 have been impacted by drilling brine, that had likely been emplaced prior to the extension of the borehole. Tracer analysis (uranine and tritium) of U-tube samples suggests significant contamination of drill brine (37% to 100%; Table 11). Chemical and isotopic analysis of the U-tube samples also indicates mixtures of drill fluid and formation waters. Trace amounts of methane and higher hydrocarbons were also found in the U-tube samples, and the ratio of methane to ethane and propane suggests the gases are not likely bacteriogenic.

Comparison of crush and leach results for deep water samples at High Lake and Lupin (Stotler et al., 2009) shows similarities between the sites. Dilute matrix fluids are similar between the two sites, although δ^{37}Cl at High Lake is more isotopically enriched and has a greater range of δ^{37}Cl values than δ^{37}Cl measured at the Lupin site. The similarity between the sites was somewhat expected, as pre-metamorphosed sediments at Lupin were likely derived from volcanogenic greenstone belts such as High Lake. An important aspect of this study is the illustration that drilling salt contamination in permafrost remains a major restriction to date for investigating permafrost impacts on groundwater chemistry. The recommendations listed above for future investigations should aid in minimizing the contamination of samples with drilling brine, and the potential for the DBA approach to provide high quality chemical samples, if drill brine contamination and sample line freezing can be prevented, has been demonstrated.

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REFERENCES

BGC Engineering Inc. 2005. Permafrost Monitoring Results, High Lake Project, NU. Draft Report prepared for Wolfden Resources Ltd., November 4, 2005.

Bottomley, D., Clark, I. Battye, N., and Kotzer, T. 2005. Geochemical and isotopic evidence for a genetic link between Canadian Shield brines, dolomitization in the Western Canada Sedimentary Basin, and Devonian calcium-chloridic seawater. Canadian Journal of Earth Sciences, 42(11): 2059-2071.

Bottomley, D., Chan, L.H., Katz, A., Starinsky, A., and Clark, I.D. 2003. Lithium isotope beochemistry and origin of Canadian Shield brines. Groundwater, 41(6): 847-856.

Bottomley D. J., Katz A., Chan L. H., Starinsky A., Douglas M., Clark I. D., and Raven K. G. 1999. The origin and evolution of Canadian Shield brines: evaporation or freezing of seawater? New lithium isotope and geochemical evidence from the Slave Craton. Chemical Geology, 155: 295–320.

Cameron, E.M. and Ballantyne, S.B. 1975. Experimental hydrogeochemical surveys of the High Lake and Hackett River Areas, Northwest Territories. Geological Survey of Canada Paper 75-29.

Davis, W.J. 1991. Granitoid geochemistry and Late Archean crustal evolution in the central Slave Province. PhD. Dissertation, Dept. of Earth Sciences, Memorial University, St. John's, Newfoundland, 324p.

Franklin, J.M., Lydon, J.W., and Sangster, D.F. 1981. Volcanic-associated massive sulphide deposits. Economic Geology 75th Anniversary Volume, 75; 485-627.

Frape, S.K. and Fritz, P. 1987. Geochemical trends for groundwaters from the Canadian Shield. *In* Saline Water and Gases in Crystalline Rocks, P. Fritz and S.K. Frape eds. GAC Special Paper 33: 19-38

Frape, S.K., Blyth, A., Blomqvist, R., McNutt, R.H., and Gascoyne, M. 2003. Deep Fluids in the Continents: II. Crystalline Rocks. Treatise on Geochemistry, v.5: 541-580.

Frape, S.K., Stotler, R.L., Ruskeeniemi, T., Ahonen, L., Paannanen, M., and Hobbs, M.Y. 2004. Hydrochemistry of Groundwaters at and below the base of the permafrost at Lupin: Report of Phase II. OPG Supporting Technical Report No: 06819-REP-01300-10047-R00.

Freifeld, B.M., Trautz, R.C., Kharaka, Y.K., Phelps, T.J., Myer, L.R., Hovorka, S.D., and Collins, D.J. 2005. The U-tube: a novel system for acquiring borehole fluid samples from a deep geologic CO2 sequestration experiment. Journal of Geophysical Research, 110-B10203.

Freifeld, B.M. and Trautz, R.C. 2006. Real-time quadropole mass spectrometer analysis of gas in borehole fluid samples acquired using the U-tube sampling methodology. Geofluids, v. 6: 217-224.

Freifeld, B.M., Finsterle, S., Onstott, T.C., Toole, P., and Pratt, L.M. 2008a. Ground surface temperature reconstructions using in situ estimates for thermal conductivity acquired with a fiber-optic distributed thermal perturbation sensor. Geophy. Res. Letters. 35; L14309.

Freifeld, B.M., Chan. E., Onstott, T.C., Pratt, L.M, Johnson, A., Stotler, R., Holden, B., Frape, S., Pfiffner, S.M., DiFurio, S., Ruskeeniemi, T., Neill, I. 2008b. Deployment of a deep borehole observatory at the High Lake Project site, Nunavut, Canada. International Conference on Permafrost (ICOP) Proceedings. 9; 469-474.

Gartner Lee, Ltd. 2005. Field Report, High Lake Project, Hydrogeology 2005. Prepared for Wolfden Resources Inc. Report GLL 51-025.

Gartner Lee, Ltd. 2006a. High Lake Environmental Assessment, Appendix A: Hydrogeological Modelling of the Proposed High Lake Mine. Prepared for Wolfden Resources Inc. Report GLL 41-120.

Gartner Lee, Ltd. 2006b. Field Report, High Lake Project, Hydrogeology 2006. Prepared for Wolfden Resources Inc. Report GLL 61-014.

Gartner Lee, Ltd. 2006c. Draft Field Report – High Lake Project Surface Water Hydrology 2004 & 2005. Prepared for Wolfden Resources Inc., GLL 51009.

Gartner Lee, Ltd. 2006d. Field Report High Lake Project Water and Sediment Quality – 2004-2005. Prepared for Wolfden Resources Inc, GLL 51009.

Gaucher, E.C., Blanc, P., Bardot, F., Braibant, G., Buschaert, S., Crouzet, C., Gautier, A., Girard, J.-P., Jacquot, E., Lassin, A., Negrel, G., Tournassat, C., Vinsot, A., and Altmann, S. 2006. Modelling the porewater chemistry of the Collovian-Oxfordian formation at a regional scale. Geochemistry, v. 338**:** 917-930.

Harris, R.N. & Chapman, D.S. 1997, Borehole temperatures and a baseline for 20th-Century global warming estimates, Science, 275, 1618–1621.

Henderson, J.R., Henderson, M.N., Kerswill, J.A., Arias, Z. Lemkow, D., Wright, T.O. and Rice, R. 1993: Geology and mineral occurrences of the southern part of High Lake greenstone belt, Slave Province, Northwest Territories; in Current Research, Part C; Geological Survey of Canada, Paper 93-1C;125-136.

Henderson, J.R., Henderson, M.N., and Kerswill, J.A. 1994. Geology and Mineral Occurrences of High Lake greenstone belt, Archean Slave Province, NWT: a preliminary account of an unconformity between two volcanic sequences; in Current Research 1994-C; Geological Survey of Canada, p. 81-90.

Henderson, J.R., Kerswill, J.A., Henderson, M.N., Villeneuve, M., Petch, C.A., Dehls, J.F., and O'keefe, M.D. 1995. Geology, geochronology, and metallogeny of High Lake greenstone belt, Archean Slave Structural Province, Northwest Territories. Current Research 1995-C. Geological Survey of Canada: p. 97-106.

Henderson, J.R., Henderson, M.N., and Dehls, J.F. 2000. Geology, High Lake greenstone belt, Nunavut. Geological Survey of Canada, “A” Series Map, Report: 1945A, 1 sheet.

Hoffman, P. 1992. Slave craton and environs. District of Mackenzie, Northwest Territories. Geological Survey of Canada, Open File Map 2559, scale 1:1,000,000.

Jeng, M. 2006. Hot water can freeze faster than cold?!? American Journal of Physics 74 (6): 514

Kleespies, P.A. 1994. The geology and geochemistry of gold mineralization, Ulu Claims, Northwest Territories, Canada. M.Sc. Thesis, Dept. of Geology, University of Alberta, 217p.

Kusky, T.M. 1989. Accretion of the Archean Slave province. Geology, v. 17: 63-67.

Lachenbruch, A.H. & Marshall, B.V. 1986. Changing climate: geothermal evidence from permafrost in the Alaskan Arctic, Science, 234, 689–696.

Lambie, K.E. 2008. Experiment and the use of Geochemical Analyses for the Purpose of Matrix Pore Fluid Extraction and Characterization: A Case Study for Radioactive Waste Disposal. Department of Earth and Environmental Sciences: University of Waterloo: Ph.D.Thesis.

Lorenson, T.D., M.J. Whiticar, A. Waseda, S.R. Dallimore, and T.S. Collett. 1999. Gas composition and isotopic geochemistry of cuttings, core, and gas hydrate from the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well. In Scientific Resutls from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, Geological Survey of Canada Bulletin 544, S.R. Dallimore, T.Uchida, and T.S. Collett, eds, pp: 143-163.

Mazurek, M. 2000. Geological and hydraulic properties of water-conducting features in crystalline rocks. In *Hydrogeology of Crystalline Rocks*, I Stober and K. Bucher (eds), Kluwer Academic Publishers, Water Science and Technology Library, v. 34: 3-26.

Milkov, A.V., Claypool, G.E., Lee, Y.-J., Torres, M.E., Borowski, W.S., Tomaru, H, Sassen, R., Long, P.E., and ODP Leg 204 Scientific Party. 2004. Ethane enrichment and propane depletion in subsurface gases indicate gas hydrate occurrence in marine sediments at southern Hydrate Ridge, offshore Oregon. Organic Geochemistry, v. 35: 1067-1080.

Milkov, A.V., Claypool, G.E., Lee, Y.-J., and Sassen, R. 2005. Gas hydrate systems at Hydrate Ridge offshore Oregon inferred from molecular and isotopic properties of hydrate-bound and void gases. Geochimica et Cosmochimica Acta, 69(4): 1007-1026.

NWMO 2005.Choosing a way forward: The future management of Canada’s used nuclear fuel. Nuclear Waste Management Organization. (Available at www.nwmo.ca).

O’Keefe, M.D. 1996. Structural Geology of the Metasediemtary Rocks in the Northern Part of the Archean High Lake Greenstone Belt, Slave Province, N.W.T., Canada. Thesis. Department of Geological Sciences: Queen’s University.

Petch, C.A. 2004. The Geology and Mineralization of the High Lake Volcanic-hosted Massive Sulfide Deposit, Nunavut. Exploration Mining Geology: 13 (1-4): pp. 27-47.

Pfiffner, S., Onstott, T.C., Ruskeeniemi, T., Talikka, M., Bakermans, C., McGown, D., Chan, E., Johnson, A., Phelps, T., LePuil, M., DiFurio, S., Pratt, L., Stotler, R., Telling, J., Sherwood Lollar, B., Niell, I., and Zerbin, B. 2008. Challenges for Coring Deep Permafrost on Earth and Mars. Astrobiology, 8(3): 1-57.

Ruskeeniemi, T., Paananen, M., Ahonen, L., Kaija, J., Kuivamäki, A., Frape, S., Moren, L., and Degnan, P. 2002. Permafrost at Lupin, Report of Phase I. Geological Survey of Finland, Nuclear Waste Disposal Research Report YST-112.

Ruskeeniemi, T., Ahonen, L., Paananen, M., Frape, S., Stotler, R., Hobbs, M., Kaija, J., Degnan, P., Blomqvist, R., Jensen, M., Lehto, K., Moren, L., Puigdomenech, I., and Snellman, M. 2004. Permafrost at Lupin, Report of Phase II. Geological Survey of Finland, Nuclear Waste Disposal Research Report YST-119.

Shelton, K.L., McMenamy, T.A., van Hees, E.H.P., and Falck, H. 2004. Deciphering the complex fluid history of a Greenstone-Hosted gold depost: Fluid incluision and stable isotope studies of the Giant Mine, Yellowknife, Northwest Territories, Canada. Economic Geology, v. 99: 1643-1663.

Sherwood Lollar., B., Frape, S.K., Weise, S.M., Fritz, P., Macko, S.A., and Wlhan, J.A. 1993a. Abiogenic methanogenesis in crystalline rocks. Geochimica et Cosmochimica Acta, v. 57: 5087-5097.

Sherwood Lollar, B., Frape, S.K., Fritz, P., Macko, S.A., Welhan, J.A., Blomqvist, R., and Lahermo, P.W. 1993b. Evidence for bacterially generated hydrocarbon gas in Canadian Shield and Fennoscandian Shield rocks. Geochimica et Cosmochimica Acta, v. 57: 5073-5085.

Sherwood Lollar, B., Weise, S.M., Frape, S.K., and J.F.Barker. 1993c. Isotopic constraints on the migration of hydrocarbon and helium gases of southwestern Ontario. Bulletin of Canadian Petroleum Geology. 42 (3) 283-295.

Shouakar-Stash, O. 2008. Evaluation of Stable Chlorine and Bromine Isotopes in Sedimentary Formation Fluids. Ph.D. Thesis. Department of Earth and Environmental Sciences: University of Waterloo.

Smellie, J.A.T., Waber, H.N., and Frape, S.K. 2003. Matrix fluid chemistry experiment, Final Report, June 1998-March 2003. SKB Technical Report TR-03-18, 162p.

Starinsky, A., and Katz, A. 2003. The Formation of Natural Cryogenic Brines. Geochimica et Cosmochimica Acta, 67(8): 1475–1484.

Stotler, R.L., Frape, S.K., Ruskeeniemi, T., Ahonen, L., Paannanen, M., Hobbs, M.Y., and Zhang, M. 2009. Hydrochemistry of Groundwaters at and below the base of the permafrost at Lupin: Report of Phase III. NWMO Technical Report TR-2009-10.

Waber, H.N. and Frape, S.K. 2002. Djupförvarsteknik matrix fluid chemistry experiment, Synthesis Report: Drillcore pore water leaching studies and borehole water. SKB Technical Document TD-03-02, 67p.

Zerbin, B. 2006. Personal communication. Drill Forman, Major Drilling Corp.