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Energy Resources Conservation Board

AGS Alberta Geological Survey

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Acknowledgments

We thank the County of Strathcona for allowing Alberta Geological Survey (AGS) to drill two testholes at the Hastings Lake Community Hall site. E. Parks helped with field and core sampling, and patiently carried out the thermal-conductivity measurements. N. Atkinson described the core samples of the Quaternary drift. S. Fitzgerald carried out the sensitivity analysis of conductive heat flow to different sediment and rock types as a summer student project at AGS during the summer of 2008. A. Barker (Alberta Environment) produced the refined bedrock topography and drift thickness maps for the Edmonton area. D. Magee provided graphics support. Comments and suggestions by T. Lemay helped improve the manuscript. Funding for this project was provided by the Alberta Department of Energy through an Alberta Energy Innovation Fund grant.

Abstract

Albertans increasingly make use of ground-source geothermal energy to heat and cool houses, farms and public and commercial buildings. Alberta Geological Survey (AGS) therefore initiated a project to assess the importance of geoscience information for the cost-effective and safe implementation of closed-loop ground-source geothermal (geoexchange) systems, which are the most commonly installed systems in Alberta.

A desktop study confirmed our belief that geoscience information, such as surficial geology, bedrock geology, depth to groundwater, depth to bedrock, thermal conductivity, transmissivity and hydraulic conductivity, is valuable in the planning, site characterization, design, installation and operation of a geoexchange project. The study identified a particular need for information on the geology (thickness and composition) of Alberta's preglacial and Quaternary drift deposits, because their character and thickness vary to a much greater extent than do those of the bedrock formations, making it more difficult to predict drilling conditions and thermal properties in a given area. Since drilling cost is the most significant financial factor in the execution of a geoexchange project, surficial geology, drift lithology and drift thickness maps that can be translated easily into 'drillability' or 'ease-of-drilling' maps can be of great assistance.

A thermal conductivity survey of surficial and shallow bedrock materials was initiated in the Edmonton area (NTS 83H) to test the feasibility of translating geological maps into maps of thermal properties. In the first year, we compiled existing geological information and focused on the acquisition of new data through drilling, sampling and thermal testing.

Two shallow boreholes (52.1 and 122.8 m) were drilled, cored and tested for their thermal properties at the Hastings Lake Community Hall east of Edmonton. The results of the in situ formation thermal-conductivity (FTC) tests revealed a higher thermal conductivity in the 42.4 m of drift sediments than in the underlying bedrock of the Horseshoe Canyon Formation.

In-house testing of thermal properties using new equipment was partly successful in that it produced results within the published ranges of thermal conductivity for the water-saturated sediment and rock types tested. A preliminary calculation of the thickness-weighted average thermal conductivity of the deep borehole (HL-08-02) came reasonably close to the thermal conductivity measured in situ using the formation thermal-conductivity (FTC) test. The methods for testing core samples of unsaturated sediments and rocks still need to be refined and improved.

A simple modelling exercise demonstrates that knowledge of the thermal properties of the ground is important because they determine 1) the amount of heat energy that can be extracted, 2) the rate at which it can be extracted, and 3) the size of the area around the extraction point that will be affected by the operation of the geoexchange system. Other factors, such as design parameters (relative annual balance of heating and cooling loads, ground-loop configuration, heat-pump efficiency, type of borehole grout, individual borehole configuration) and economic parameters (cost of electricity and natural gas, drilling costs, etc.) can have a significant effect on the cost and operation of a geoexchange system. Reliable geoscience information on the type, composition, thickness and thermal properties of the geological materials that will be penetrated will provide the greatest value by keeping drilling costs to a minimum.

1 Introduction

Ground-source geothermal energy is being used in Alberta to heat and cool houses, farms and public and commercial buildings. The number of applications is small compared to the number of dwellings that use natural gas for heating, but the number of geothermal installations is growing quickly. Using ground-source geothermal energy for heating and cooling in Alberta replaces costly natural gas, which can then be used for other purposes. As well, increased use of geothermal energy may contribute to the overall reduction of greenhouse-gas emissions in Alberta.

Discussions with geothermal-energy contractor associations and with representatives from different levels of government (municipal, provincial, federal) indicate that geoscience information is important for selecting, properly designing and implementing ground-source geothermal-energy (geoexchange) systems. Geoscience information is also critical for resolving land-use issues and potential environmental concerns related to the widespread adoption of this technology.

An assessment of the need for and importance of geoscience information in the successful implementation of geoexchange systems (groundwater open-loop geoexchange systems were not included at this time) was conducted to determine what role AGS can play in providing this information to industry, government and Albertans.

The variability of geological materials at the surface and at depth manifests itself in the form of differing drilling conditions and differing values of thermal conductivity and thermal diffusivity. Geological maps show the types of soil, sediment and bedrock that are likely present at most locations in Alberta. However, translation of these maps into useful information for geoexchange practitioners is limited because 1) published values correlating thermal properties (thermal conductivity and diffusivity) with geological material type vary quite widely, and 2) the geological material classification does not necessarily provide useful information for assessing drillability of soil and rock layers

In August 2007, AGS initiated a pilot project involving the gathering of shallow temperature and thermal conductivity measurements in shallow-earth materials (surficial sediments, shallow bedrock units) in Alberta. The aim of this activity was to test the hypothesis that thermal conductivity values correlate with geological material type and that existing geological maps of surficial material can be used to estimate thermal conductivity where no publicly accessible values exist.

The project concept entailed 1) measuring the thermal properties of rock and sediment samples collected from outcrops and surface exposures, and 2) comparing averaged values of thermal properties derived from core samples in purpose-drilled boreholes to actual in situ measurements of thermal properties measured by standard methods in those same boreholes.

In addition, we explored the relevance of geology for the operation of a geoexchange system with a simple modelling exercise and calculated the cost effects of overestimating the thermal conductivity of a site.

This report presents the results of these activities.

2 Summary of Geoexchange Technology and Status of the Industry in Alberta

2.1 Geoexchange Technology

Geoexchange is the process of extracting low-grade heat from the Earth (soil, rock, groundwater, surface water, ocean, waste heat) and transforming it using heat pump technology to higher grade heat for conditioning buildings, domestic water heating or process heating. Geoexchange technology relies on a specific application of refrigeration principles for moving heat energy from one location to another. By moving heat instead of converting chemical energy into heat (i.e., burning fossil fuels), geoexchange systems can often be more energy efficient for space heating or cooling than conventional combustion or electrical-resistance space-heating systems.

Geoexchange systems consist of three primary subsystems, as shown in Figure 1 and described below:

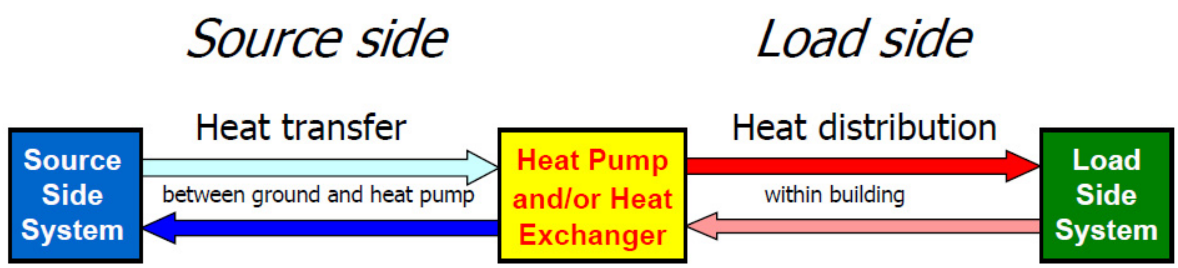


Figure 1. Three primary subsystems in a geoexchange system.

Source-side system: The thermal exchange coupling with the Earth, known as the *ground-heat exchanger* (GHX), allows heat transfer between the ground and the heat-pump system (ground coupling). In heating mode, heat is extracted from the ground through the GHX. In cooling mode, heat is transferred to the ground through the GHX.

Heat-pump–heat-exchanger system: This system uses the principles of refrigeration to move heat across temperature gradients. These components thermally transform the building's heating and cooling loads into a form the source side can accommodate by supplying heat in heating mode and receiving heat in cooling mode.

Load-side system: This is the distribution system that moves heat throughout the building and is generally referred to as the heating, ventilating and air-conditioning (HVAC) system.

Each of the three main subsystems can be designed and configured in many ways.

The industry typically places a marketing focus on the heat-pump equipment in the geoexchange system. The importance of the source side (GHX) and load side of the system, which directly affect the overall geoexchange *system energy efficiency*, is frequently underestimated. The focus of this study is on the source side (GHX) of the system.

Ground-heat exchangers (GHX) can be broadly grouped into the following types (Figure 2):

Closed loop: heat exchanged conductively with the Earth from pipes arranged in a closed circuit with a continuously circulating antifreeze solution (Figure 2a–e [left side])

Open loop: heat exchanged with water (groundwater, surface water or ocean water) pumped from the Earth to a heat exchanger or heat pump, then returned to a different disposal point (hence a discontinuous circuit, or open loop; Figure 2d, e [right side])

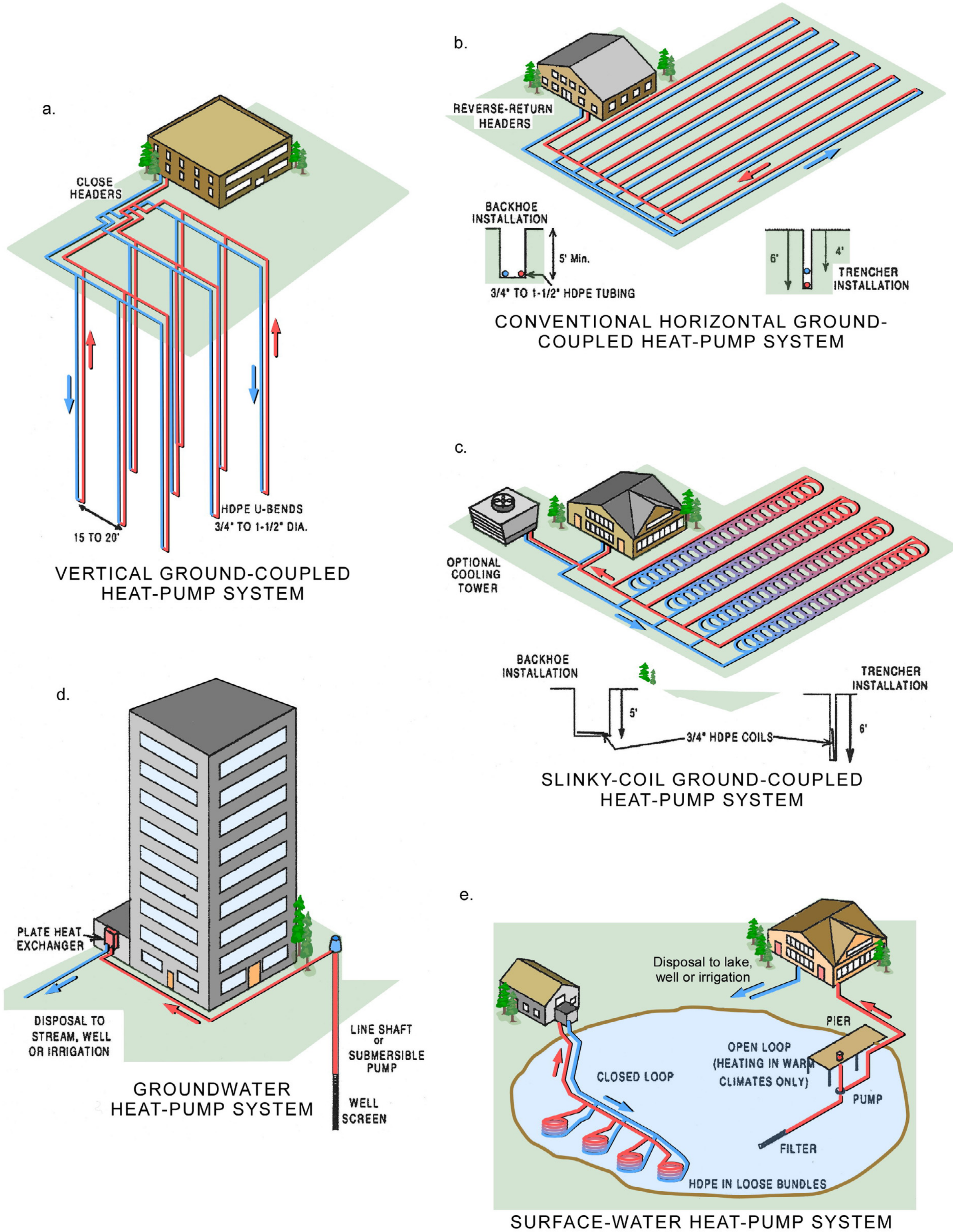


Figure 2. Typical ground-coupling options for geoexchange systems (*modified from* Kavanaugh and Rafferty, 1997).

Waste-heat coupling: heat exchanged conductively with a man-made fluid stream (e.g., treated sewage effluent or landfill leachate) to a heat exchanger, typically with a secondary loop conveying heat to the load, so that there is no direct contact between the liquid stream and the heat-exchange fluid

Hybrid coupling: heat exchanged in combination with another heating or cooling source (combined with a cooling tower, boiler or solar collector), or as a crossover between open- and closed-loop configurations (e.g., standing column well).

In Alberta, most geoexchange applications are closed-loop systems (Table 1) installed in trenches or shallow boreholes (usually less than 50 m deep). There is the potential for suitable applications of deep vertical-borehole systems (greater than 50 m deep) for industrial, commercial and larger district residential complexes, or for other specific reasons.

Table 1. Closed-loop geoexchange systems.

Type	Description
Trench (Figure 2b, c)	Ground coupling by an array of plastic pipe laid straight (single or multiple pipes) or in coils (‘slinky’ coils) within trenches typically 1.5–2.5 m (5–8 ft.) below grade; requires a large site footprint compared with other GHXs; this category would also pertain to earth tubes (subsurface horizontal tubes for preheating ventilation make-up air)
Shallow borehole (Figure 2a)	Ground coupling by an array of shallow boreholes, nominally up to 50 m (165 ft.) deep with plastic-pipe U-tubes grouted in, connected to header pipes; requires a moderate site footprint; this category would also pertain to energy piles (plastic-pipe heat exchanger incorporated into building foundation piles)
Deep borehole (Figure 2a)	Ground coupling by an array of deep boreholes, nominally >50 m (165 ft) deep with plastic-pipe U-tubes grouted in, connected to header pipes; requires a smaller site footprint than trench or shallow-borehole systems
Surface water (Figure 2e [left])	Ground coupling by a loosely bundled coil of plastic pipe, or a plate-style heat exchanger directly submerged in a body of water (ocean, lake or river), typically with shallow buried header and transfer piping to the point of use; typically requires a water body at least 4 m (16 ft) deep

2.2 Status of the Geoexchange Industry in Alberta

The size of the geoexchange industry is difficult to determine precisely. A review of Alberta yellow page listings in 2008 suggested that perhaps 30–50 geoexchange installers are active in Alberta (although it is likely that a majority of installations are installed by fewer than a dozen contractors).

The geoexchange industry in Canada is represented on a national level by the Canadian Geoexchange Coalition (CGC). The CGC has implemented standardized designer and installer training and certification programs, and a registry for recording system installations. Since mid-2008, geoexchange systems must be installed by CGC-trained and -certified installers and be recorded in the system registry to be eligible for federal ecoEnergy rebates.

On a provincial level, the Alberta Geothermal Energy Association (AGEA) was founded in March 2007. According to their website, their goal is to act as a provincial voice for the geothermal industry in Alberta by providing advocacy to the provincial and municipal governments, promoting provincial standards and responsible practices, and advancing the deployment of ground-source heat-pump technology in Alberta. The AGEA currently has about 70 members and has active linkages with the International Ground Source Heat Pump Association (IGSHPA) based at Oklahoma State University in Stillwater, Oklahoma.

3 Assessing the Value of and Need for Geoscience Information

3.1 User Groups

The main potential user groups of geoscience information in the geoexchange industry are as follows:

- **Drilling contractors:** stand-alone drilling firms engaged entirely or part-time in geoexchange drilling, primarily for closed-loop vertical-borehole GHX fields; water-well drillers are also engaged to drill supply and injection wells for open-loop groundwater-based GHXs
- **Excavation contractors:** firms engaged in trenching or excavating for the installation of trench-based closed-loop GHXs
- **Heat-pump installation contractors:** firms generally focusing on the heat pump and related hardware, they may subcontract others to install the GHX (commonly the case for single-family residential installations)
- **Design engineers:** typically consulting engineers involved in the design and specification of the GHX or entire geoexchange system
- **Design-build firms:** integrated service firms that combine contracting services (e.g., drilling) with engineering design and construction oversight, as well as project financing; such firms may be engaged for commercial-scale systems or district energy systems (DES)
- **Energy utilities:** private energy utility groups who aim to finance, own and operate geoexchange systems (typically large commercial-scale systems or DES)
- **Municipalities or municipal districts:** local government groups (engineering departments) interested in tracking the growth of the geoexchange industry and managing the density and type of installations through bylaws or zoning
- **Industry associations:** groups, such as the Alberta Geothermal Energy Association and the Canadian Geoexchange Coalition, with an interest in disseminating information (including geoscience) that would support the industry
- **Academic institutions:** training and research professionals in trade colleges or universities interested in incorporating geoscience information into geoexchange curricula
- **Provincial government groups:** groups such as the Alberta Ministries of Environment, Energy and Sustainable Resource Development, as well as Alberta Geological Survey, all directly or indirectly engaged in tracking, managing or regulating aspects of the geoexchange industry
- **Federal government groups:** organizations, including Natural Resources Canada and the Geological Survey of Canada, that are interested in characterizing thermal resources in Alberta and Canada

3.2 Value of Geoscience Information for Geoexchange Purposes

A geoexchange project can be divided into five stages with four key roles for those involved in the project. Each role at different stages has varying needs for geological information. Table 2 outlines the stages and key information needs of the geoexchange industry. In general, the primary geoscience needs for closed-loop geoexchange systems can be summarized as follows:

- depth to bedrock
- bedrock type (lithology)
- overburden type (surficial and drift geology)
- depth to groundwater (hydrogeology)
- thermal properties (including thermal conductivity, thermal diffusivity and deep ground temperature)
- ease of drilling and construction

Table 3 summarizes the relative importance and benefits of the information (uses).

In summary, the geoexchange industry benefits from geoscience information that helps facilitate the following three key steps:

- Informed selection of the types of GHX that may be feasible at a specific site and which of the potential options may be most favourable for the site setting
- Constructability evaluation of selected or short-listed GHX options for purposes of estimating costs or for adjusting GHX configurations to improve constructability
- Evaluation of thermal exchange properties for earth materials at specific sites

Each of these three steps can have a substantial effect on costs and the efficiency of the geoexchange system and, to be useful, each step requires accurate geoscience information. Where small systems are being considered (e.g., most domestic installations in Alberta), the availability of publicly available geoscience data can assist significantly in the design and implementation of GHX systems.

However, as useful as geological maps and other geoscience information resources can be for assisting 'desktop' or preliminary evaluations, it is important to recognize that test drilling and testing of in situ thermal properties are often warranted for large systems or where uncertainty warrants further detailed investigation to support detailed design.

3.3 Geoscience Data Gaps

In general, the geoexchange industry in Alberta will gain more benefit from geoscience information pertaining to Alberta's drift deposits than it will from information about the underlying bedrock. This is because the characteristics of the sedimentary bedrock are sufficiently consistent across a broad swath of central and eastern Alberta. Most experienced drillers and geoexchange designers are familiar with characteristics of the earth materials once the bedrock contact is reached.

Table 2. Geoscience information required for different stages of geoexchange projects.

Project Stage	Concept Developer	Designer	Contractor/Driller	Commissioning/ Performance Verification Agent
1) Predesign-planning	Broad-scale generalized map-view presentation of information suitable for preliminary evaluation	Designer typically seeks as much detail as can be obtained from public-domain sources, including finer scale surficial and bedrock geology maps, geological reports, water-well or other borehole drilling logs, and site-specific geotechnical reports	Detailed and reliable drift thickness maps, detailed and reliable drift composition maps, and bedrock geology maps	n/a
2) Site suitability–testing	n/a	Detailed, accurate and reliable site-specific surficial geology, bedrock geology and hydrogeology information	As above	n/a
3) Design	n/a	As above	n/a	n/a
4) Implementation	n/a	As above	As for *Predesign-planning*	Similar to *Designer* needs
5) Commissioning–post-commissioning	n/a	n/a	n/a	n/a

Abbreviation: n/a, not applicable

Table 3. Benefits and uses of geoscience information at different stages of geoexchange projects.

Project Stage	Concept Developer	Designer	Contractor/Driller	Commissioning/ Performance Verification Agent
1) Predesign-planning	Broad evaluation of whether a site is favourable for geoexchange, what types of geoexchange are possible, which types may be most favourable, and the range of potential cost	*Concept Developer* may consult with *Designer* to conduct a more comprehensive predesign-planning evaluation for predicting suitability of geoexchange options, predicting performance, and estimating range of installation cost	Geoscience information is vital for the drilling contractor to preliminarily evaluate the most appropriate drill method and to estimate the cost for installation	n/a
2) Site suitability–testing	n/a	At this step, geoscience information is assessed to identify data gaps and to prescribe additional site-specific investigations to address gaps	Geoscience information is used to prepare quotes to conduct test drilling and to select most appropriate drill methods	n/a
3) Design	n/a	Geoscience information acquired from literature sources, combined with information obtained from site-specific investigations, is crucial for developing reliable and cost-effective designs	n/a	n/a
4) Implementation	n/a	Geoscience information may be helpful in interpreting variability or unusual ground conditions encountered during implementation	Geoscience information may be helpful in interpreting variability or unusual ground conditions encountered during implementation	Geoscience information may be useful for evaluating actual ground-heat exchanger performance with the anticipated design performance
5) Commissioning–post-commissioning	n/a	Geoscience information may be used for verifying design parameters or as part of system diagnostics to identify and interpret conditions that may be contributing to an underperforming ground-heat exchanger	n/a	Geoscience information may be used for verifying design parameters or as part of system diagnostics to identify and interpret conditions that may be contributing to an underperforming ground-heat exchanger

Abbreviation: n/a, not applicable

In contrast, the character and thickness of the drift deposits varies significantly across small distances because of the complex glacial deposition history of the region. Therefore, reliable information about drift deposits is (or ought to be) particularly relevant to the geoexchange designer and contractor. It is important to note, however, that representatives of the geoexchange industry stress that geoscience information will be useful and valued only if the information is detailed and reliable. Consequently, because the drift deposits vary so much, significant future effort will be required to compile reliable and useful information for surficial materials that will be broadly accepted by the geoexchange industry.

3.4 New or Expanded Geoscience Products

From discussions with representatives of the geoexchange industry, we conclude that new or expanded geoscience products that would be helpful for the Alberta geoexchange industry include mapping of

- **Drift-deposit isopachs**: Properly used, this information could significantly benefit the geoexchange designer and/or contractor. For closed-loop vertical-borehole GHX systems, the drift interval will usually be the most uncertain and often the most challenging portion of the borehole because of the high variability of materials, which affects drilling and completion conditions and the prediction of thermal conditions.
- **Buried bedrock channels**: Buried bedrock channel aquifers are common across the Canadian Prairies. The presence of these channels can cause significant thickening of the drift deposits along the channel. These deposits may include layers that can be quite difficult to drill. These conditions can result in less favourable conditions for closed-loop borehole types of geoexchange systems, while offering conditions that are more favourable for groundwater open-loop types of GHX (that may be able to produce groundwater from basal gravel beds within the channel).
- **Groundwater-resource potential**: The information requirements for evaluating the potential to adopt open-loop groundwater GHX systems, although not considered during the present study, are similar to the requirements for evaluating any other use of groundwater.
- **Presence of artesian flow, shallow gas or other unusual features**: Maps showing information relating to the presence of unusual or potentially hazardous conditions could benefit geoexchange designers and may help avoid unwise designs or construction practices.

4 Thermal-Conductivity Survey of Surficial Materials in the Edmonton Area

A pilot-study approach was used to investigate the feasibility of translating geological maps into maps of geothermal properties. The Edmonton area (NTS 83H; Figure 3) was selected for the pilot study because of a wealth of pre-existing geological information in the form of surficial geology and industrial-minerals maps, Quaternary drillhole data, and water-well drillers' logs (e.g., McPherson and Kathol, 1972; Andriashek, 1983).

The activities in 2007–2008 consisted of the compilation of existing geological information and focused on the acquisition of new data through drilling, sampling and thermal testing.

4.1 Sampling of Surficial Materials in the Edmonton Area Reconnaissance

Alberta Geological Survey executed several legs of a reconnaissance field-sampling program to collect samples of different types of surficial materials at 10 sites (29 samples) in the Edmonton area for analysis of lithological and thermal properties.

The sampling strategy was to focus on representative samples of the surficial materials, such as glacial till, lacustrine silty clay and eolian sand (Appendix 1), which underlie most of the Edmonton area. Sampling was conducted with a split-spoon probe that could provide samples from depths of up to 1.3 m. With the exception of an unweathered till sample taken from a fresh roadcut (Figure 4), all samples were within the zone of weathering, which might affect their thermal-conductivity characteristics.

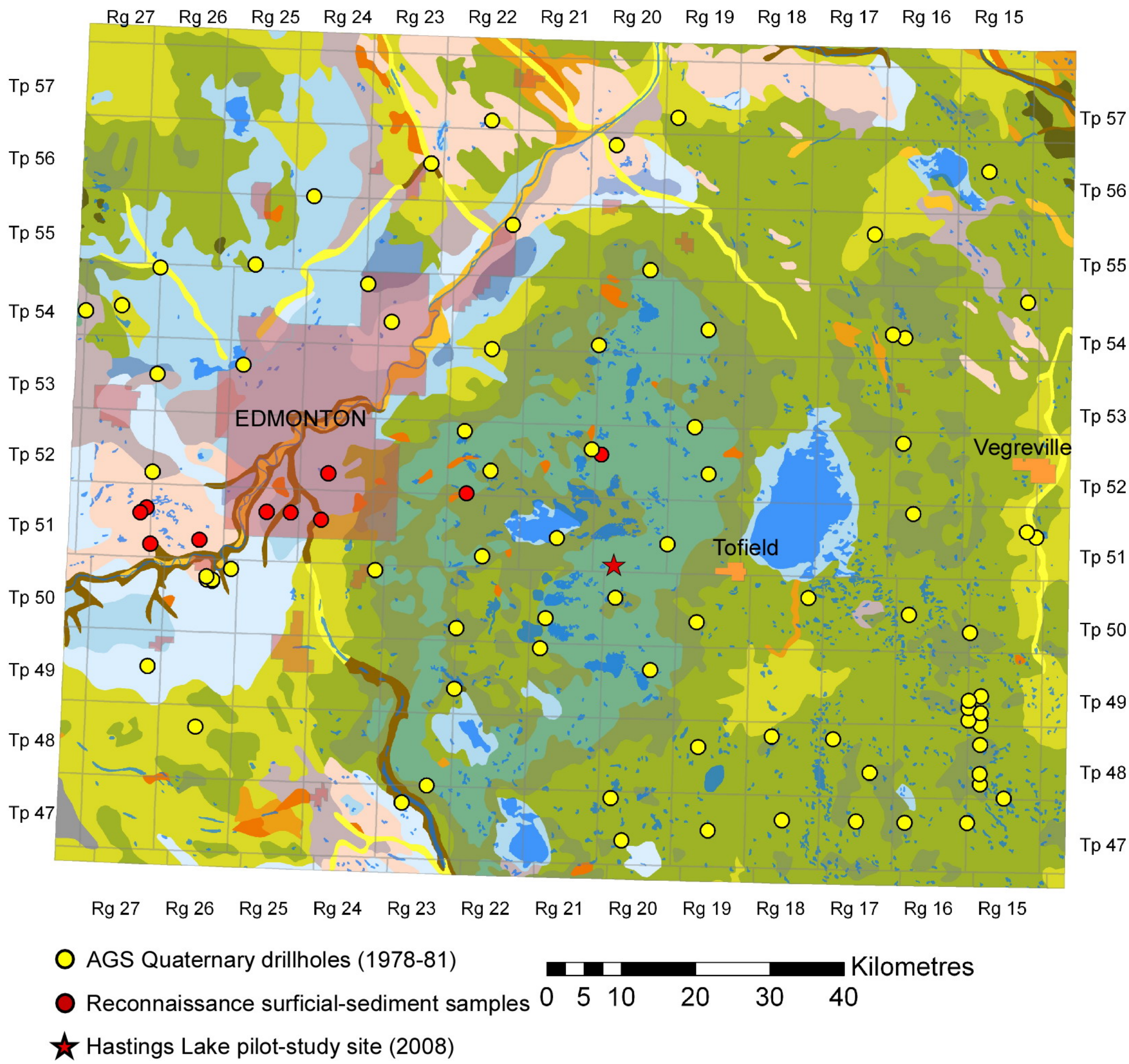


Figure 3. Surficial geology of the Edmonton 1:250 000 map area (NTS 83H), with locations of Quaternary drillholes (1978–1981), surficial-sediment samples (2007) and the geothermal drilling at the Hastings Lake Community Hall site (2008).

4.2 Hastings Lake Drilling Project

The goal of the drilling project was to investigate the properties of shallow geological materials (in an area of thick drift over bedrock) in the Edmonton area with regard to the installation and performance of closed-loop vertical-borehole geoexchange systems. The study included drilling, coring and geophysical logging of surficial and bedrock materials, as well as in situ thermal-property testing. Results will be used to help calibrate existing geological maps and to provide information for geoexchange application.

After review of available geological information and consultation with landowners, the Hastings Lake Community Hall, owned and operated by the County of Strathcona, was selected as the site for the pilot drilling study (Figure 5). The County was very open to the idea of investigating the option of retrofitting

Figure 4. Surficial-material sample site TC-07-4 (Appendix 1) provided an unweathered till sample from a depth of 4.5–4.75 m.

the facility with a geoexchange heating and cooling system in the future, since the existing two forced-air gas furnaces (~20 years old) are due for replacement in the near future.

Two boreholes (‘shallow’ and ‘deep’) were drilled and cored at the site using the mud-rotary drilling method with a Christensen core-barrel system. The shallow borehole ‘HL08-01’ was drilled and completed to a depth of 52.1 m (171 ft.). The deep borehole ‘HL08-02’ was drilled and completed to a total depth of 122.8 m (400 ft.). Both boreholes were completed as ground-heat exchangers by installing u-bend heat-exchange tubing (U-tubes) and grouting (Figure 6).

Soils encountered included drift sediments, consisting of silt, sand, clay and gravel, overlying Horseshoe Canyon Formation bedrock at a depth of about 43 m (140 ft) in both boreholes (Figure 6; Appendices 2, 3). Core recovery from the drift sediments overlying the bedrock was very poor (<10%), whereas recovery from the bedrock was generally better than 80%. The Horseshoe Canyon Formation bedrock consists of interbedded sandstone, siltstone, shale, bentonite and coal (Appendix 3). The drillcore was wrapped in plastic wrap and aluminum foil to prevent it from drying out, placed in core boxes and transported to the AGS Minerals Core Storage Facility (MCRF) to prevent it from freezing.

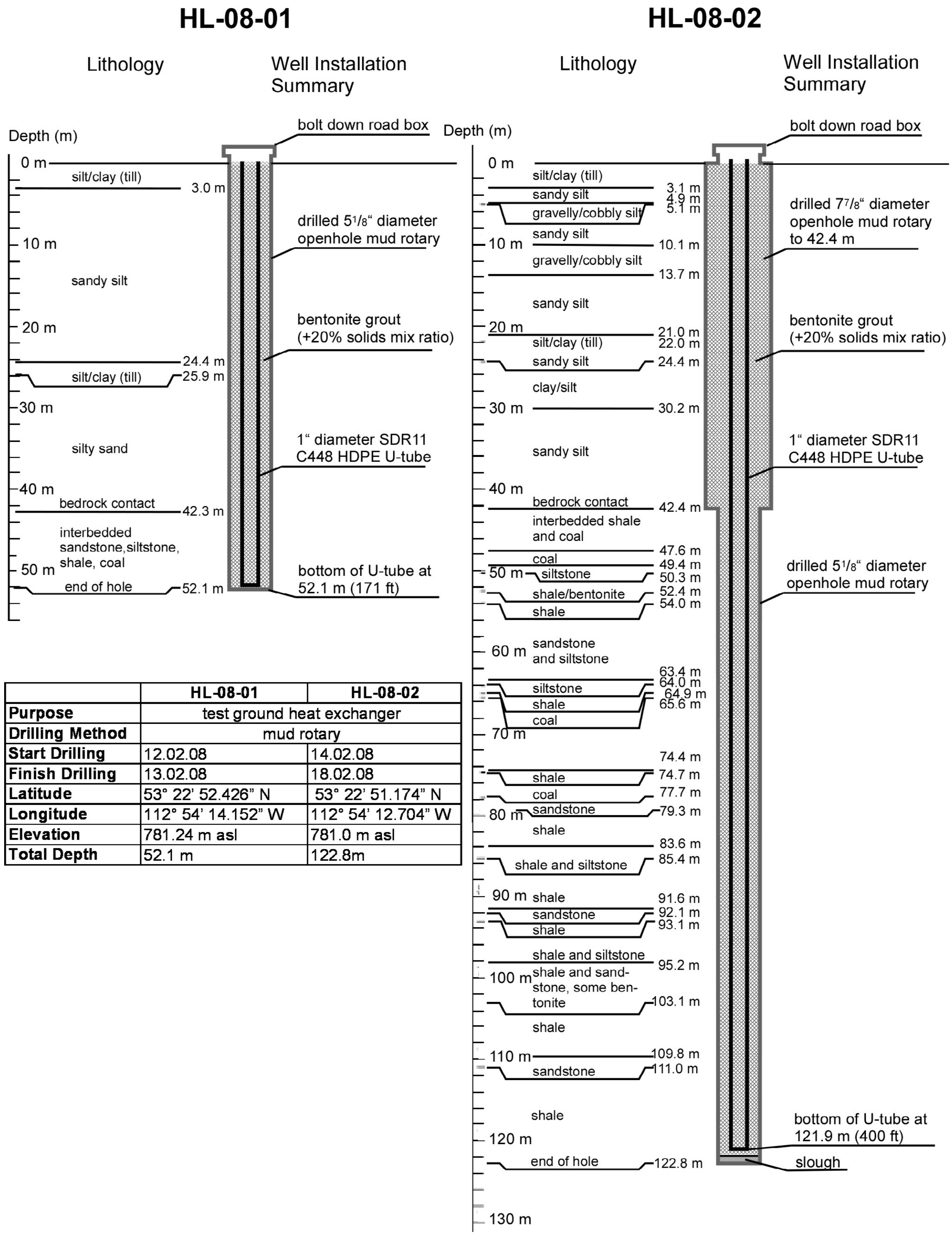
Prior to U-tube installation in the deep borehole, downhole geophysical logging was conducted. Zones of instability were encountered in both boreholes within the upper drift sediments, at the bedrock contact and in coal zones within the bedrock. The drift (overburden) warrants particular attention at this site because it

Figure 5. Hastings Lake Community Hall with drill rig in background and u-bend heat-exchange tubing (U-tubes) being prepared for installation.

is quite thick and many zones within the drift sediments were loose and unstable. Successful drilling and construction of closed-loop vertical-borehole heat exchangers in these conditions requires greater skill and attention to detail than in other areas where the drift is thinner or more stable.

Thermal profiling and formation thermal-conductivity (FTC) testing were conducted on both the shallow (HL08-01) and deep (HL08-02) borehole heat exchangers. The temperature data collected with two different temperature probes immediately prior to FTC testing on March 3, 2008 show offsets of up to 0.5°C at similar depths between the shallow and deep boreholes (Figure 7).

To determine whether a real offset existed, we took an additional set of temperature measurements with the same temperature probe on March 27, 2008. These measurements show no temperature offset between the shallow and deep boreholes in the upper 40 m, suggesting that no actual offset exists. Compared to the results from March 3, however, the temperatures measured on March 27 are about 0.75°C higher in both boreholes. We attribute this to residual heat in the ground from the FTC tests carried out between March 3 and 5, which involved circulating heated water through the U-tubes. Therefore, the temperature measurements taken in the deep borehole on March 3 likely establish the most accurate temperature profile for the drill site. This temperature profile shows a relatively constant temperature of 6.1°C from surface to a depth of about 25 m, then cooling by about 0.4°C down to about 50 m and then a steadily increasing temperature to a maximum of 7.5°C at the bottom of the borehole.



	HL-08-01	HL-08-02
Purpose	test ground heat exchanger	
Drilling Method	mud rotary	
Start Drilling	12.02.08	14.02.08
Finish Drilling	13.02.08	18.02.08
Latitude	53° 22' 52.426" N	53° 22' 51.174" N
Longitude	112° 54' 14.152" W	112° 54' 12.704" W
Elevation	781.24 m asl	781.0 m asl
Total Depth	52.1 m	122.8m

Figure 6. Geological log and well-installation summary for shallow (HL-08-01) and deep (HL-08-02) boreholes at the Hastings Lake Community Hall site.

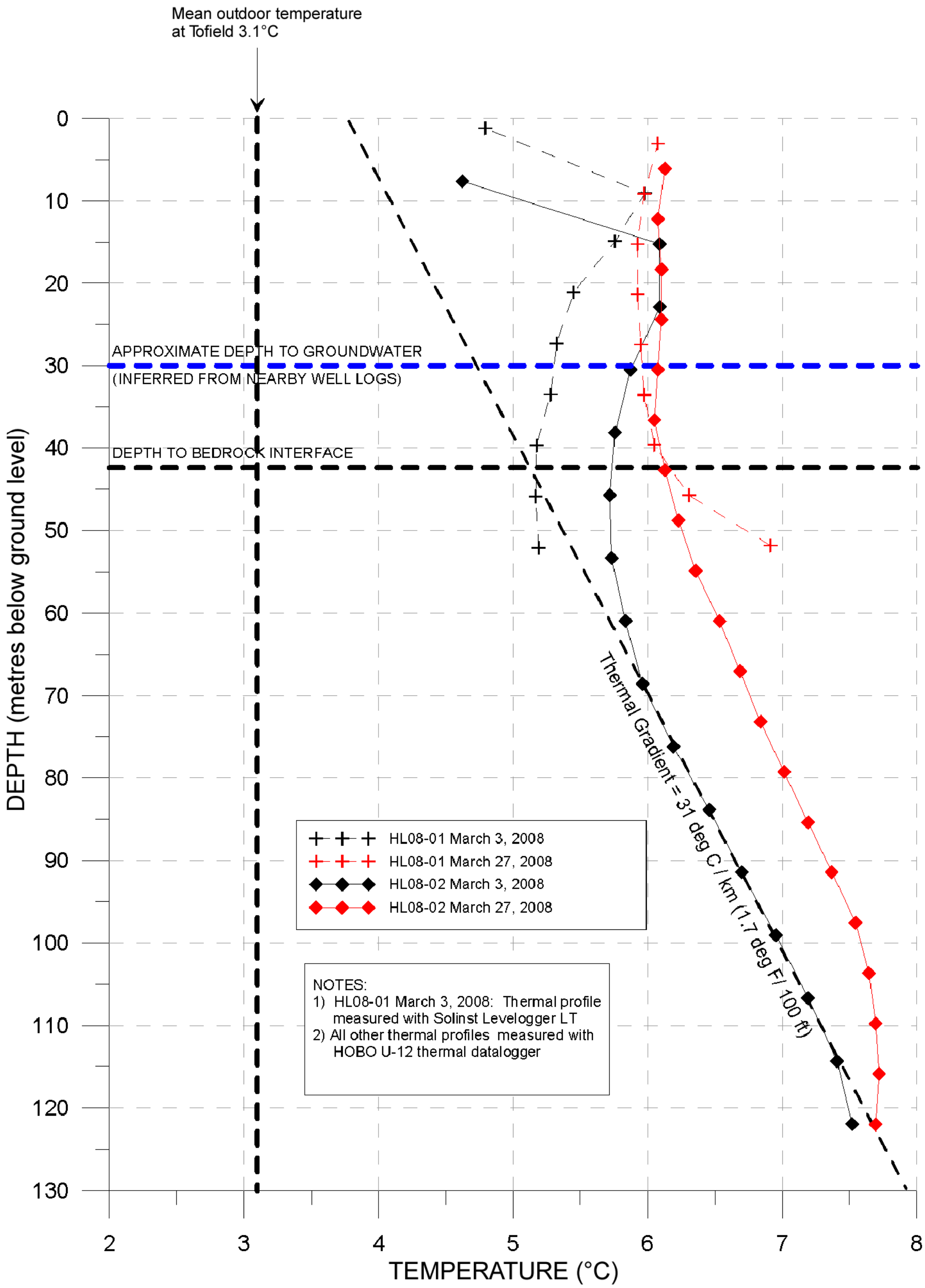


Figure 7. Thermal-profile results for shallow (HL08-01) and deep (HL08-02) boreholes. Mean outdoor temperature at Tofield taken from Environment Canada Climate Normals, 1971–2000 (Environment Canada, 2001).

The relationship between air temperature and ground temperature is complex and depends on many factors, of which snow cover, type of vegetation, topography, wind exposure, ground cover and ground moisture are important (Majorowicz, 1993).

The relatively high temperature of 6.1°C in the upper 25 m of the deep borehole compared to the multi-annual mean outdoor temperature of 3.1°C measured at the closest weather station in Tofield, about 15 km east of the drill site (Environment Canada Climate Normals, 1971–2000), may be due to

- increased incident solar radiation to the ground surface after clearing of trees when the site was developed (directly adjacent to an outdoor tennis court, which may act as a solar heat sink; Majorowicz, 1993);
- the insulating effect of snow cover, which may serve to reduce heat loss from the ground during extreme cold weather (Judge, 1973; Lewis and Wang, 1992); or
- the possibility that the 3.1°C mean outdoor temperature was lower during the period 1971–2000 than from 2000 to the present.

When extrapolating the calculated geothermal gradient defined by the data below 70 m to the ground surface, it intersects the ground surface at approximately 3.7°C, which is similar to the 1971–2000 mean outdoor temperature (Figure 7).

Thermal-profile results indicate mean borehole temperatures of 6.1°C and 6.8°C at HL08-01 and HL08-02, respectively (Figure 7). These values fall within the temperature range that Majorowicz et al. (2009) gave for the upper 150 m in this area of Alberta, based on their analysis of well temperature versus depth logs from the Canadian temperature data collection at the Geological Survey of Canada (GSC) in Calgary.

The FTC testing on both boreholes was carried out following the methods and procedures described in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) guidelines (Kavanaugh, 2000). It involved the circulation of water, to which a known amount of heat energy was applied, through the U-tube over periods of 42 hours in HL-08-01 and 60.5 hours in HL-08-02, and measuring the temperature of the water at the inlet and the outlet of the U-tube (Appendices 4 and 5). The results were analyzed using two separate methods (Table 4): the line-source linear approximation (Austin, 1998) and a software numerical analysis method developed by the United States Department of Energy (Shonder and Beck, 2000).

Table 4. Summary of thermal-conductivity test results. The standard unit for thermal conductivity is W/(m•K), where W is the energy rate or power (in watts or joules per second), m is length (in metres) and K is change in absolute temperature (in degrees Kelvin).

Method	Parameter	Shallow Borehole (HL-08-01)	Deep Borehole (HL-08-02)
Linear approximation	Thermal conductivity (W/m•K)	2.01	1.74
Numerical analysis	Thermal conductivity (W/m•K)	1.81	1.59
Linear approximation	Thermal diffusivity (m^2/day)	0.08	0.072
Numerical analysis	Borehole resistance (m•K/W)	0.13	0.19

The line-source method is the most common method used to analyze FTC test data and is reliable for tests conducted with consistent power input (standard deviation less than 1.5% of the average power input (Q) and maximum deviation is less than 10% Q). For the Hastings Lake tests, the standard deviations were 0.57% Q and 0.37% Q, respectively, for the shallow and deep boreholes, and the maximum deviations were 0.97% Q and 0.66% Q, respectively, indicating that the line-source method should provide reliable results. In a study of various heat-conduction models, Gehlin and Hellström (2003) compared the results of four different published models for analyzing thermal-conductivity test data. The line-source model showed the closest agreement to measured temperature-response data, and the Shonder and Beck (2000) model agreed to within 4% of the temperature-response data. Gehlin and Hellström (2003) concluded that the line-source method is the fastest and simplest model, and that numerical models are best suited for situations with variable heat injection. For the Hastings Lake tests, the numerical analysis method was used primarily as a verification check and provided thermal-conductivity values that were about 10% lower than those calculated by the line-source method.

Formation thermal-conductivity test results (Table 4; Appendices 4, 5) indicate thermal conductivities of 2.01 W/m•K for HL08-01 (dominated by shallow drift deposits) and 1.74 W/m•K for HL08-02 (drift and bedrock).

The results suggest that the average thermal conductivity for the drift sediments is slightly higher than that for bedrock but that the undisturbed deep ground temperature is slightly higher in the bedrock. Groundwater can affect thermal conductivity in a number of different ways, with saturated materials having a higher conductivity than nonsaturated materials and groundwater flow resulting in advective heat loss (Chiasson et al., 2000). At the test site, materials were saturated (except very near the surface) and groundwater flow was not evident, leading us to discount the effect of advective heat loss.

The thermal-conductivity result from HL08-01 is within the typical range for a silt and sand (Witte et al., 2002). The result for HL08-02 is slightly lower than that for HL08-01, indicating that the thermal conductivity of the bedrock is less than that of the drift sediments at this location. This is surprising because we expected that the denser, consolidated bedrock types (with the exception of the coal) would have higher thermal conductivities than the unconsolidated drift sediments.

This observation could be attributed to one or both of the following conditions:

- presence of considerable amounts of coal in the bedrock portion of HL08-02 (coal, which makes up about 10% of the bedrock portion encountered, is a relatively poor thermal conductor)
- low thermal performance of the siltstone and shale in the bedrock portion of HL08-02 due to fracturing and preglacial weathering

Consequently, the total required bore length to support a given heating or cooling load is expected to be quite similar for boreholes constructed completely in drift compared to those constructed in both drift and bedrock (assuming borehole spacing is the same), at least at this location.

4.3 Thermal-Conductivity Results

4.3.1 Thermal-Properties Testing of Earth Materials

The goal of this activity was to collect thermal-properties measurements for different types of Alberta's surface and subsurface earth materials (sediments, rocks) to test the utility of producing thermal-property maps.

The planned approach was to 1) obtain thermal-property values of rock and sediment samples collected from outcrops and core samples from purpose-drilled boreholes and 2) compare the average thermal properties from core samples to actual values measured by standard in situ methods in the same boreholes.

In order to carry out measurements of thermal properties of earth materials, AGS purchased a Mathis TCi™ portable thermal-conductivity analyzer (Figure 8).

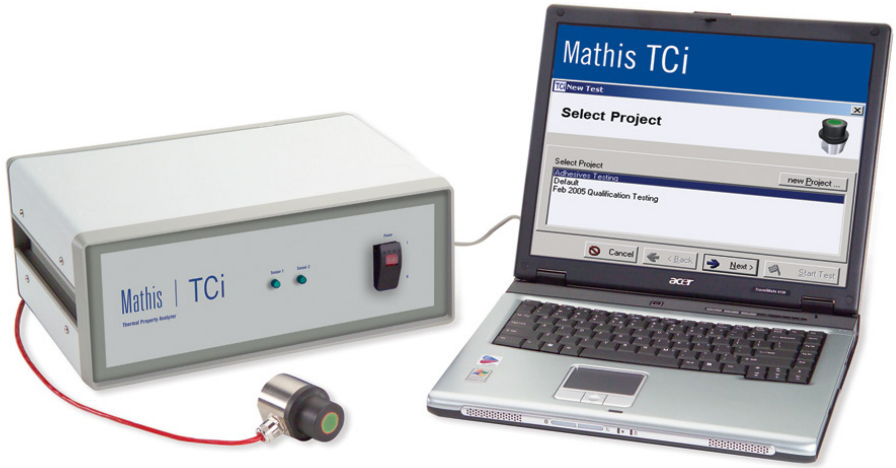


Figure 8. Mathis TCi thermal-conductivity analyzer (image reproduced with permission from C-Therm Technologies Ltd.).

The thermal-conductivity analyzer is based on the modified transient-plane-source technique (Gustafsson, 1991; Mathis, 1999, 2000). It uses a one-sided, interfacial, heat-reflectance sensor that applies a brief, constant heat pulse to the sample. The heat provided results in a rise in temperature at the interface between the sensor and the sample. This temperature rise at the interface induces a change in the voltage of the sensor element. The rate of increase in the sensor voltage is used to determine the thermophysical properties (thermal conductivity and effusivity) of the sample material. The thermophysical properties of the sample material are inversely proportional to the rate of increase in the sensor voltage: the more thermally insulative the material, the steeper the increase in voltage. The analysis is nondestructive but requires a flat contact surface between the sample and the sensor. Slight sample-surface irregularities are compensated for by the use of a contact agent (usually water). The Mathis TCi is certified by the Canadian Standards Association (CSA), and certification of compliance with the standards of the American Society for Testing and Materials (ASTM) is pending (Mathis Instruments, 2009). Precision and accuracy of measurements conducted on standard materials that were provided by the manufacturer are better than 1% and better than 5%, respectively. A comparison of the Mathis TCi with the ASTM certified standard guarded hot-plate method (American Society for Testing Materials, 1985) showed that the results agree to within 2% (Canney et al., 2001).

To the best of our knowledge, this study is the first that uses the Mathis TCi for the measurement of thermal conductivity on rocks and sediments, which are inherently heterogeneous.

Testing was carried out on a variety of earth materials (sediments and rocks). In order to produce a flat contact surface, unconsolidated but cohesive sediments were cut with a knife and rocks were cut with a rock saw. Cuts were oriented perpendicular to bedding. Dry rock samples were resaturated with distilled water overnight. The samples were placed on the TCi sensor with three drops of water as a contact agent. Ten consecutive measurements were taken before moving on to the next sample. Since evaporation and capillary uptake of the contact agent during the testing time (about 10 minutes) generally result in a lowering of thermal conductivity with time, a test was declared valid when more than four consecutive measurements fell within ±2.5% of their mean value.

Results from testing fully saturated rocks and competent sediments fall within the range of literature values (Birch and Clark, 1940; Kappelmeyer and Haenel, 1974; Roy et al., 1981; Cermak and Rybach, 1982; Robertson, 1988; Zoth and Haenel, 1988). Testing partially saturated or unsaturated rocks and sediments led to unreliable results with poor repeatability and values that fell outside the published ranges. Therefore, it was not possible to obtain reliable measurements for the surficial sediment samples collected in the reconnaissance field-sampling program (*see* Section 4.1). Alberta Geological Survey subsequently purchased an additional calibration unit and accessories for handling loose materials and fluids for the thermal-conductivity analyzer. Further testing will be required to develop a procedure that will yield more reliable and accurate results for these types of earth materials, which are of particular importance to the shallow geothermal resource. This will include more detailed sample analysis (texture, mineralogy) and the verification of measured values by application of a different method for the same samples. Once the analytical process and methodology have been worked out satisfactorily, AGS plans to build a database of thermal-property values for Alberta earth materials.

4.3.2 Thermal Conductivity of Sediments and Rocks at the Hastings Lake Pilot Site

Thermal-conductivity measurements were obtained from nine core samples of the drift sediments and 66 core samples of the Horseshoe Canyon Formation (Appendix 6). As mentioned earlier, the drillcore had been wrapped in plastic wrap and aluminum foil to prevent it from drying out. Core intervals were individually unwrapped and samples were taken from the centre of the core. Samples of drift sediments were quickly weighed (for determination of moisture content) and immediately placed on the TCi sensor for thermal analysis. Bedrock samples were placed directly on the sensor without weighing. Samples were visually inspected and classified into broad lithological categories (i.e., sand, silt, clay, sandstone, siltstone, shale, coal, bentonite) prior to thermal analysis. Detailed textural (grain size, sorting, porosity) and compositional (mineralogy) analyses of the samples are still outstanding, and will refine lithological classification of the samples.

Measured thermal conductivities for the recovered drift sediments (classified as sand, silt and clay) ranged between 1.8 and 3.2 W/m•K, with an average of 2.4 W/m•K (Table 5). However, given the poor core recovery (<10% of 42.4 m) in the unconsolidated drift sediments (i.e., cored intervals are mostly more competent, clay-rich silt and clay, while the less competent sand and gravel were washed out during drilling), the samples were not deemed to be representative of the sediment types encountered. As a result, a thickness-weighted average of thermal conductivity for the drift sediments could not be obtained. Moisture contents ranged from 8.2 wt. % in silty sand recovered at 10.65 m depth to 21 wt. % in silty clay from 5.9 m depth (Table 6). For the silt samples except sample 1, a general trend of decreasing thermal conductivity with increasing moisture content can be observed. The low conductivity of sample 1, taken at 0.3 m depth, may be due to the effects of weathering and the presence of distributed organic matter.

Table 5. Ranges and averages of measured thermal conductivity (k) for sediment and rock types cored at the Hastings Lake Community Hall site. Drift-sediment samples were recovered from borehole HL-08-01, bedrock samples from boreholes HL-08-01 and HL-08-02.

Lithology	Max. k (W/m•K)	Min. k (W/m•K)	Avg. k (W/m•K)	No. of Samples
Sand[1]	2.5	2.5	2.5	1
Silt[1]	3.2	1.8	2.4	7
Clay[1]	2.2	2.2	2.2	1
Sandstone	2.7	1.8	2.1	25
Siltstone	2.7	2.0	2.3	6
Shale	2.4	1.5	2.0	23
Bentonite	2.0	1.9	2.0	4
Coal	1.0	0.6	0.7	8

[1] Denotes drift sediment samples (*see also* Table 6).

Table 6. Measured thermal conductivity and moisture content for unconsolidated drift samples cored in drillhole HL-08-01 at the Hastings Lake Community Hall site.

Sample No.	Depth (m)	Moisture Content (wt. %)	Thermal Conductivity (W/m•K)	Lithology
1	0.3	11.6	1.8	sandy silt
2	0.82	13.6	2.5	silt
3	1.2	15.7	2.2	clayey silt
4	2.71	12.9	2.3	sandy silt
5	5.9	20.7	2.2	silty clay
6	10.55	9.5	2.5	silty sand
7	10.65	8.2	n/a	silty sand
8	22.6	11.5	3.2	sandy silt
9	25.7	12.8	2.9	sandy silt
10	39.5	13.9	2.2	sandy silt

Measured thermal conductivities for the recovered bedrock types range between 0.6 W/m•K for some coal samples and 2.7 W/m•K for some siltstone and sandstone samples (Table 5). Since core recovery in the bedrock units was good, we attempted to calculate a thickness-weighted average of thermal conductivity (Table 7).

Table 7. Thickness-weighted average thermal-conductivity contributions of saturated bedrock types at the Hastings Lake Community Hall site.

Lithology	Cumulative Thickness (m)	Fraction of Total Thickness	Average Thermal Conductivity (W/m•K)	Thermal-Conductivity Contribution (W/m•K)
Bentonite	0.5	0.006	2.0	0.01
Coal	7.85	0.102	0.7	0.08
Sandstone	28.05	0.364	2.1	0.78
Shale	27.49	0.357	2.0	0.71
Siltstone	13.22	0.171	2.3	0.39
Total	**77.11**	**1.000**		**1.97**

A composite thermal conductivity of 1.97 W/m•K was calculated for the 77 m of bedrock types penetrated at the Hastings Lake Community Hall site.

Due to the lack of representative samples for the drift sediments and the preliminary nature of sample lithology designation, a direct comparison of these values with those obtained from the FTC tests (*see* previous section) would be premature. However, given these uncertainties, the calculated composite thermal conductivity of 1.97 W/m•K is reasonably close to the values obtained by the FTC tests for both the shallow borehole (dominated by drift sediments; 2.01 W/m•K) and the deep borehole (43 m of drift sediments and 77 m of bedrock; 1.74 W/m•K). It appears the thermal conductivities derived from the FTC tests are lower than those that would be calculated as a composite of weighted-average values from the thermal analysis of the core samples. This is likely because the thermal-conductivity measurements were conducted on the best preserved (least disturbed) samples that could be obtained from the core. This eliminated the effect of naturally occurring, water-filled fractures (i.e., in the upper part of the bedrock section, close to the bedrock-drift interface), which would generally lower the thermal conductivity of a given sediment or rock unit (water has a thermal conductivity of 0.6 W/m•K). More opportunities for comparison of in situ FTC tests with calculated composite thermal-conductivity values derived from core samples are necessary to establish a better calibration methodology. However, the calculated composite thermal conductivity can serve as an estimate of the maximum thermal conductivity of the bedrock material at this site.

5 Relevance of Geology for the Operation of a Closed-Loop Geoexchange System

After we had obtained some real thermal-conductivity data for the Hastings Lake Community Hall pilot-study site, we set out to answer the following questions:

- How do differences in the thermal conductivities of various sediments and rocks affect the thermal performance of a closed-loop vertical-borehole geoexchange system and the potential for thermal interference between the vertical boreholes?
- Does it matter if we do not know the exact nature (and thereby the exact thermal properties) of the geological materials at a site where a geoexchange system is going to be installed? What would be the cost of overestimating the thermal conductivity of the ground at a given location?

The following two sections present results from a simple modelling exercise and a sample calculation, with which we explored these questions in more detail.

5.1 Modelling of Conductive Heat Flow

A simple one-dimensional approximation of heat flow through a homogeneous sediment or rock was used to assess the effect of lithology on the performance of a geoexchange system. This was done by assuming a semi-infinite solid, one end of which is in contact with the borehole, and the far field of the solid remaining at the initial starting temperature. By keeping the borehole end at a constant temperature of 0°C and manipulating the initial temperature throughout the solid, it was possible to simulate different temperature gradients between borehole and surrounding sediment or rock. This one-dimensional approximation is rather simplistic and does not take into account any heat generation or external heat transfer. Furthermore, it does not consider the thermal characteristics of the heat-exchange piping and grout, which are significant factors. However, it can be used to make qualitative observations and demonstrate trends in the thermal responses of different sediment and rock types.

Separate temperature-distribution curves were calculated from the thermal conductivities measured at the Hastings Lake pilot-study site for the different sediment and rock types encountered (Section 4.3.2.). The amount of energy that can be extracted from a given lithology over a given time through two boreholes spaced 30 m apart (such as in the case of the two boreholes at the Hastings Lake site) with a given temperature difference between the heat-exchange fluid and the ground was calculated (Figure 9). The results allowed the different sediment and rock types to be compared in terms of their relative energy-extraction efficiency (Figure 10). It should be noted that boreholes in most closed-loop vertical-borehole geoexchange systems are usually spaced much closer together (6–8 m).

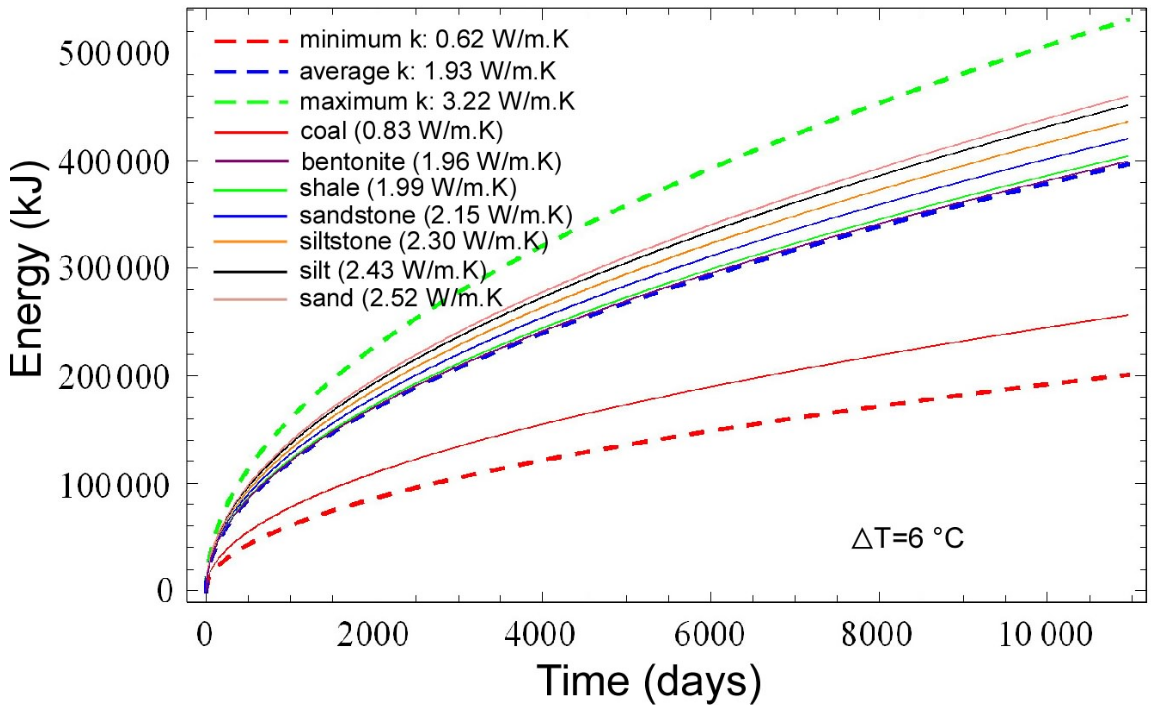


Figure 9. Amount of heat energy that can be extracted over time from sediment and rock types with different thermal conductivities in two boreholes spaced 30 m apart and with an initial temperature difference between heat-exchange fluid and surrounding lithology (ΔT) of 6°C.

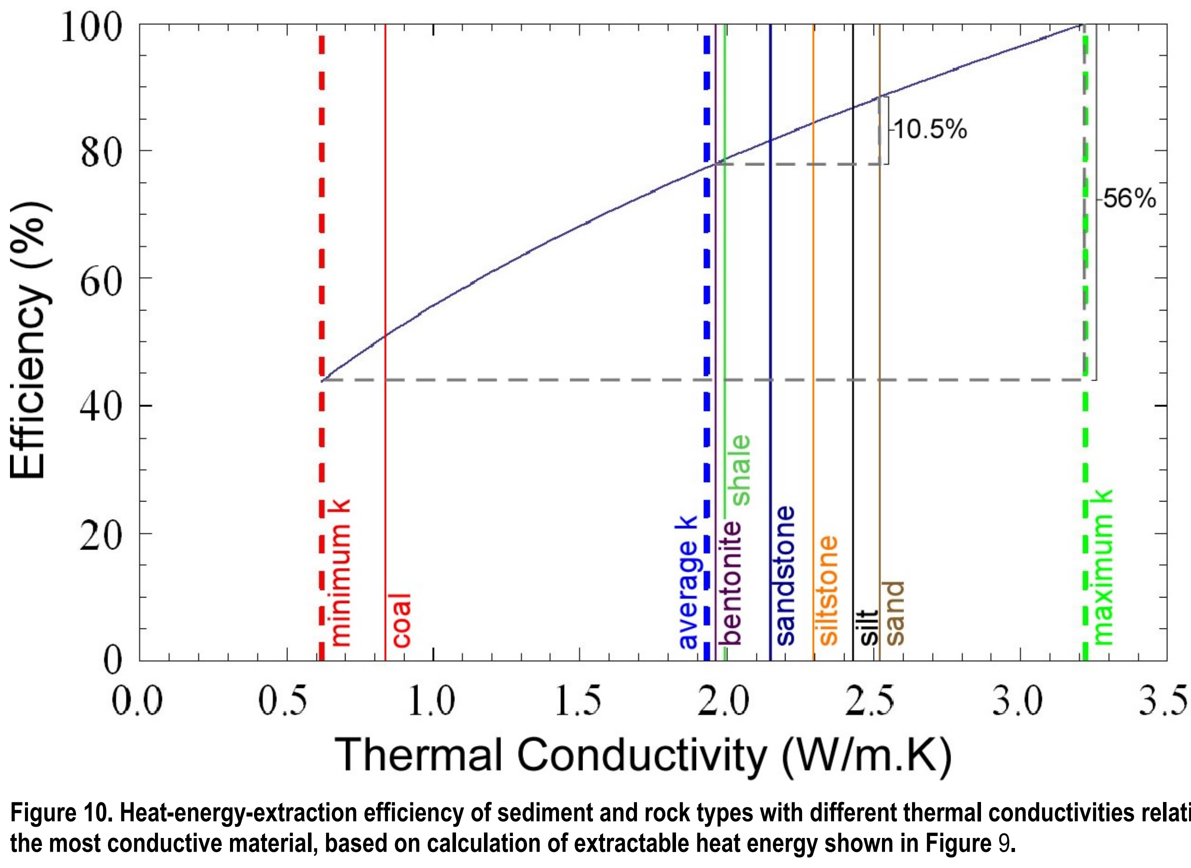


Figure 10. Heat-energy-extraction efficiency of sediment and rock types with different thermal conductivities relative to the most conductive material, based on calculation of extractable heat energy shown in Figure 9.

Taking the maximum value of heat energy extracted (i.e., for the maximum thermal conductivity of 3.22 W/m•K) after a given time (Figure 9) as 100% efficiency, the relative heat-energy-extraction efficiency for the different sediment and rock types was calculated (Figure 10). While the maximum difference of efficiency over the whole range of measured thermal conductivities (0.62–3.22 W/m•K) is 56%, the maximum difference between average thermal conductivities for most sediment and rock types (except coal) is about 10%.

The amount of extractable energy is dependent on the thermal properties of the lithology and the temperature difference between the heat-exchange fluid and the ground. For simplicity, the thermal properties of the borehole heat-exchange tubing and grout have not been taken into account. In principle, the larger the temperature difference between the fluid and the ground and the higher the thermal conductivity of the lithology, the more heat energy can be extracted. A doubling in the temperature difference, while keeping the thermal properties of the lithology constant, results in a doubling of extractable heat energy over a given time.

The minimum distance between two boreholes at which they will not interfere and the maximum time that could possibly elapse before two boreholes at a specified distance apart interfere with each other were calculated for the different sediment and rock types (Table 8; Figures 11). Interference was defined as two times the distance of the extent of the temperature disturbance from one well bore (i.e., the intersection of temperature effects between the two boreholes).

Note that the calculated values are based on the assumptions that 1) the system is continuously extracting the maximum amount of heat, 2) no heat generation or external heat transfer is occurring, and 3) the thermal properties of the borehole heat-exchange tubing and grout are not taken into account. All of these assumptions result in an overstatement of the extent of temperature effects. Therefore, whereas the overall trends are certainly valid, models that are more sophisticated should be used to arrive at times and distances that are more realistic.

Table 8. Noninterference time between two boreholes 30 m apart and noninterference distance for different sediment and rock types and continuous maximum heat-energy extraction duration of 6 months and 1 year, assuming a 6°C temperature difference between heat-exchange fluid and lithology.

Lithology	Conductivity k (W/m•K)	Noninterference time (d)	Noninterference distance (m)	
			6 months	1 year
Coal	0.84	185.8	29.7	42.1
Bentonite	1.96	82.3	44.7	63.2
Shale	1.99	81.5	44.9	63.5
Sandstone	2.15	76.0	46.5	65.8
Siltstone	2.3	71.6	47.9	67.8
Silt	2.43	68.4	49.0	69.3
Sand	2.52	66.0	49.1	70.6
Minimum	**0.62**	**208.5**	**28.1**	**39.7**
Maximum	**3.22**	**53.9**	**55.2**	**78.1**
Average	**1.93**	**83.7**	**44.3**	**62.7**

If one were to assume maximum heat-energy extraction for 6 months, without replenishment by geothermal heat from the Earth's interior and through solar irradiation, the noninterference distance between two boreholes ranges from 29.7 m for coal to 49.9 m for sand (Table 8; Figure 11). The time until thermal interference begins between two boreholes that are 30 m apart ranges from 186 days (almost exactly 6 months) for coal to 66 days for sand. For an average lithology with a conductivity of about 1.95 W/m•K, the noninterference distance is 44.3 m and the noninterference time is 84 days.

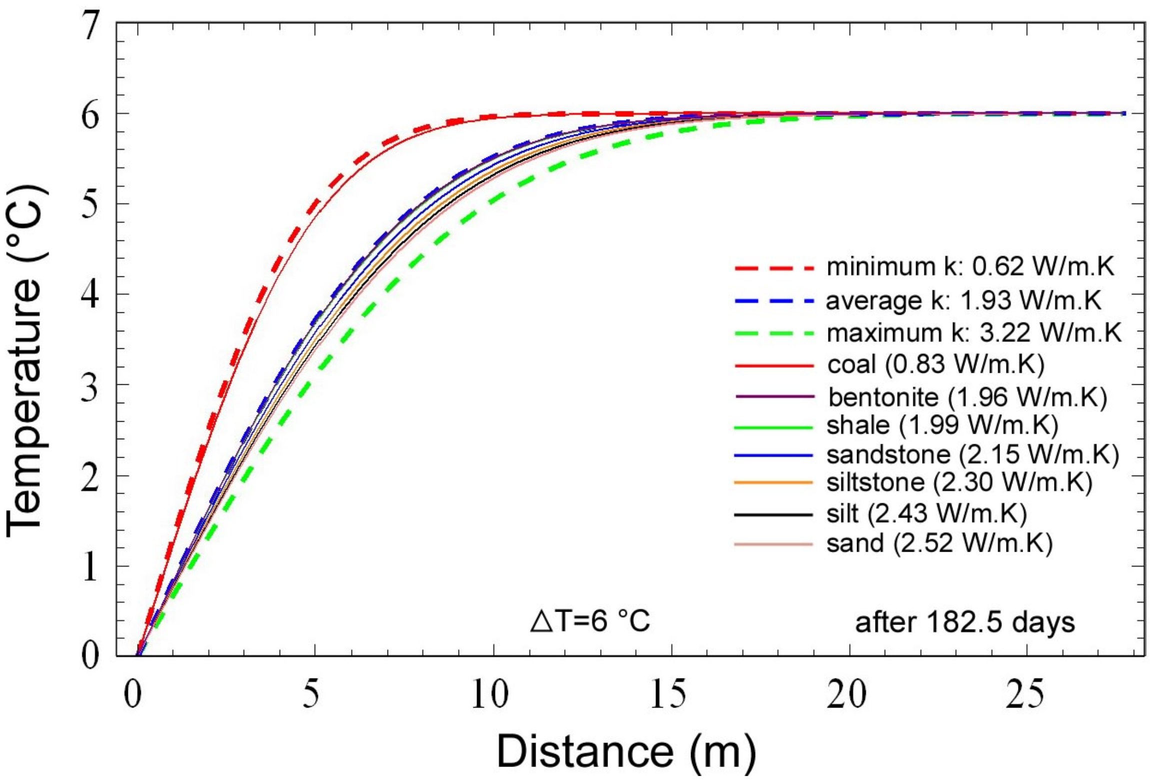


Figure 11. Temperature distribution for different sediment and rock types in the vicinity of a borehole after 6 months of continuous heat extraction assuming a 6°C temperature difference between heat-exchange fluid (borehole at left side) and lithology.

With the exception of coal, temperature distribution curves are relatively close together and noninterference time and distance values are similar, not varying by more than 11%.

As mentioned above, these calculations are oversimplified. Commercially available engineering and design software is capable of simulating the operational conditions of a geoexchange system, considering the natural design parameters of the ground-heat exchanger (GHX), as well as the heat pump and load side of the system. However, the trends outlined by our simple simulation demonstrate the effect of the thermal properties of different sediment and rock types on the amount of heat energy that can be extracted, the extraction rate and the extent of temperature change around the GHX.

5.2 Effect of Overestimating Thermal Conductivity

To investigate the cost effects of overestimating the thermal conductivity of a site, we calculated the required ground-heat-exchanger loop lengths for a heating load generated by a hypothetical 465 m^2 building at the Hastings Lake site using the software package GCHPCalc (Kavanaugh and Rafferty, 1997).

Aside from thermal conductivity, diffusivity and deep-ground temperature, factors that significantly affect the loop length are

- the relative annual balance of heating and cooling loads. This factor can affect loop lengths by a factor of 100% or more.
- the configuration of the ground loop, including the spacing between boreholes and shape of the layout pattern. Tightly spaced blocky grid patterns can require much more loop length than open-spaced linear patterns. This can affect loop length by a factor of 100% or more.
- the efficiency of the heat pump (usually expressed as coefficient of performance [COP], which is the ratio of heat output to the amount of energy input). This can affect loop length by a factor of 25% or more.
- the type of borehole grout (low solids:liquids ratio or high solids:liquids ratio). High-solids conductive grouts can reduce loop length by as much as 25%.
- the configuration of the individual borehole (including borehole diameter, pipe diameter, etc.). This factor can affect loop length by 10% or more.

Most importantly, the load must be defined reasonably accurately in terms of the instantaneous peak load (heat energy per unit time or 'power') and the long-term load (cumulative monthly and annual heat energy).

Figure 12 illustrates the heating-load requirements for the hypothetical building at the Hastings Lake site following standard procedures of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (2005). Hourly outside air-temperature data for the Edmonton International Airport from Environment Canada (2008) were used to determine the required heating load to heat the building to an indoor temperature of 20°C. The heating load is assumed to be a simple linear function of outdoor temperature, with the peak load of 0.079 kWh/m^2 at the design temperature of –30.5°C. The area below the curve in Figure 12 represents the heating energy (kWh) required to heat the building.

Using GCHPCalc design software, loop lengths were calculated for different design specifications (load requirements, bore grid patterns, bore-to-bore spacing and two different thermal conductivities; Table 9) using the following parameters:

- Loads as defined on Figure 12:
  - 100% peak load: 36.6 kW peak, 102 000 kWh annual
  - 70% peak load: 25.6 kW peak, 99 100 kWh annual
  - 50% peak load: 18.3 kW peak, 89 400 kWh annual
  - 30% peak load: 11.0 kW peak, 66 400 kWh annual

- Ground thermal properties as per shallow borehole FTC test results:
  - Thermal conductivity: $k = 1.90$ W/m•K
  - Thermal diffusivity: $\alpha = 0.08$ m^2/day
  - Average ground temperature: 6.1°C

- Heat-pump efficiency: COP = 3.7 at entering water temperature of 0°C

The results presented in Table 9 show that loop length varies significantly as parameters are varied. All scenarios provide at least 87.5% of the annual heating energy to the building (with the remainder provided by the electrical resistance heater built into the heat pump for assisting the heat pump during peak heating events). It should be noted that the loop lengths would diminish remarkably if a cooling load of significant duration were to occur, because the ground would receive additional heat energy during the summer, thereby increasing the ground temperature. Differences in calculated loop lengths for the two different thermal conductivities (measured k and higher k in Table 9) range between 60 and 260 m (between 10% and 13%) for different design scenarios.

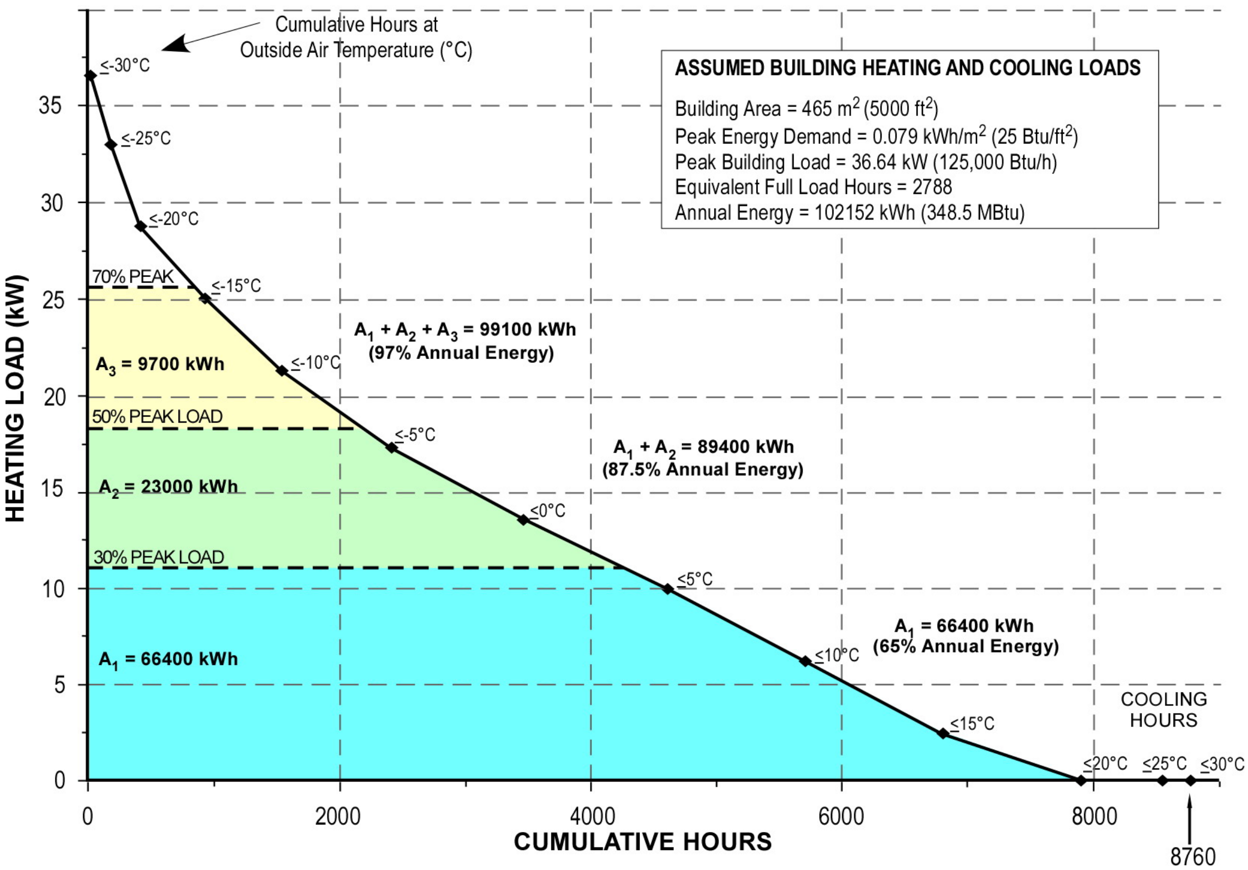


Figure 12. Required annual heating load for a hypothetical 465 m² building at the Hastings Lake site. 'Cumulative hours at outside temperature' based on data from the Edmonton International Airport weather station, reported in Environment Canada's National Climate Data and Information Archive (Environment Canada, 2008).

We back-calculated the peak load fraction served by the undersized ground loop using the highlighted scenario from Table 9. Assuming that a ground loop was designed based on the unreasonably high thermal conductivity of 2.25 W/m•K (compared to the average value of 1.9 W/m•K measured through FTC testing at the Hastings Lake pilot site),. undersizing the ground loop (through overestimating the thermal conductivity) results in a smaller portion of the peak load being met, which will have to be made up by the electrical resistance heater in the heat pump. The results indicate that the undersized ground loop would serve a peak load of 22.6 kW (62% peak) instead of 25.6 kW (70% peak). Referring to Figure 12, the annual energy (area under the curve between 25.6 and 22.6 kW) is approximately 3000 kWh or approximately 3% of the total annual heating energy demand for the building.

If the 3000 kWh were provided entirely by the heat pump at a COP of 3.7, then the cost to provide this amount of heat energy would be $81/year at an electricity cost of $0.10/kWh. However, with the undersized ground loop, the 3000 kWh shortfall would be supplied by electrical resistance heat (at a COP of 1) at a cost of $300/year. Therefore, the additional operational cost because of overestimating the thermal conductivity is $219/year.

Table 9. Examples of loop lengths required for a closed-loop geoexchange system with different load requirements, different borehole grid patterns and spacings at two different thermal conductivities (k).

Load	Borehole Grid Pattern (rows)	Bore-to-Bore Spacing (m)	Grout Conductivity (W/m•K)	Loop Length (m) at Measured k (k = 1.90 W/m•K)	Loop Length (m) at Higher k (k = 2.25 W/m•K)
100% peak, 100% annual	5 x 4 block	4.6	0.80	1850	1590
100% peak, 100% annual	5 x 4 block	6.1	0.80	1320	1170
100% peak, 100% annual	5 x 4 block	9.1	0.80	1090	980
100% peak, 100% annual	1 x 15 linear	4.6	0.80	1290	1150
70% peak, 97% annual	5 x 4 block	6.1	0.80	1060	930
70% peak, 97% annual	5 x 4 block	7.6	0.80	872	780
70% peak, 97% annual	1 x 12 linear	7.6	0.80	795	713
50% peak, 87.5% annual	3 x 3	7.6	0.80	628	560
50% peak, 87.5% annual	1 x 9	7.6	0.80	600	540

If standard geoexchange drilling were charged at $40/m, then the drilling of the additional 92 m that would have been required for a correctly sized ground loop would cost $3680. Assuming that electricity prices remain the same, the savings on not drilling the proper depth of hole would be reduced to zero after a maximum of 16 years of operation.

Since drilling cost is the overriding economic factor in the overall cost of a closed-loop vertical-borehole geoexchange system, any geoscience information that helps keep drilling costs to a minimum is valuable. This information would particularly include the type, composition and thickness of geological material that needs to be penetrated and its thermal properties.

6 Thermal-Conductivity Mapping

6.1 Pilot Study in the Edmonton Area

All available information on the geology and hydrogeology (i.e., drillhole lithologs, surficial geology maps, drift stratigraphy maps, hydrogeology maps) of the Edmonton area (NTS 83H) has been compiled to test the utility of turning geological maps into maps of geothermal properties. If the information was available only in hardcopy, it was converted to digital format to form the basis of a three-dimensional digital model of the shallow bedrock and drift sediments.

To date, integration of the lithology data from water-well drillers' reports and archived lithologs from AGS drilling projects have resulted in the refinement of the bedrock surface (Figure 13) and thus a new preliminary drift-thickness map (Figure 14) for the Edmonton area.

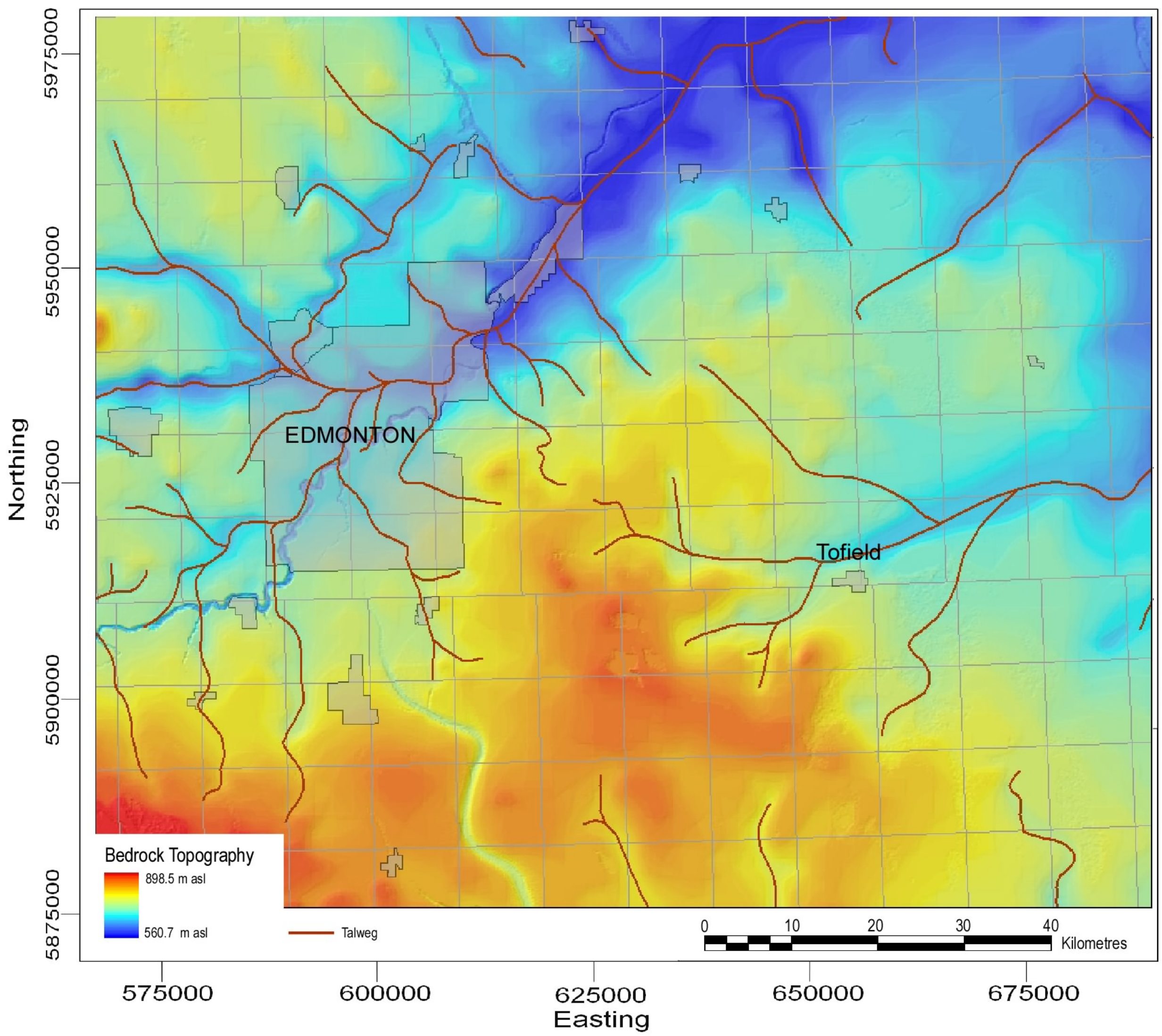


Figure 13. Refined bedrock topography and location of major talwegs in the Edmonton area (NTS 83H).

The lithology information can also be used to carry out quick assessments of the cumulative thickness of certain sediment and rock types (e.g., cumulative sand and gravel thickness; Figure 15), which has a bearing on drillability and thermal characteristics of the ground at a given location.

We still need to put in place the lithological framework, develop a reliable methodology for measuring the thermal conductivity of surficial and drift sediments, and collect a statistically significant number of measurements from the sediments and rock formations in the Edmonton area. When this work has been completed, we will be able to populate the three-dimensional geological model with thermal-conductivity values and produce a new generation of digital map products that will be of use to the geoexchange industry, governments and the public.

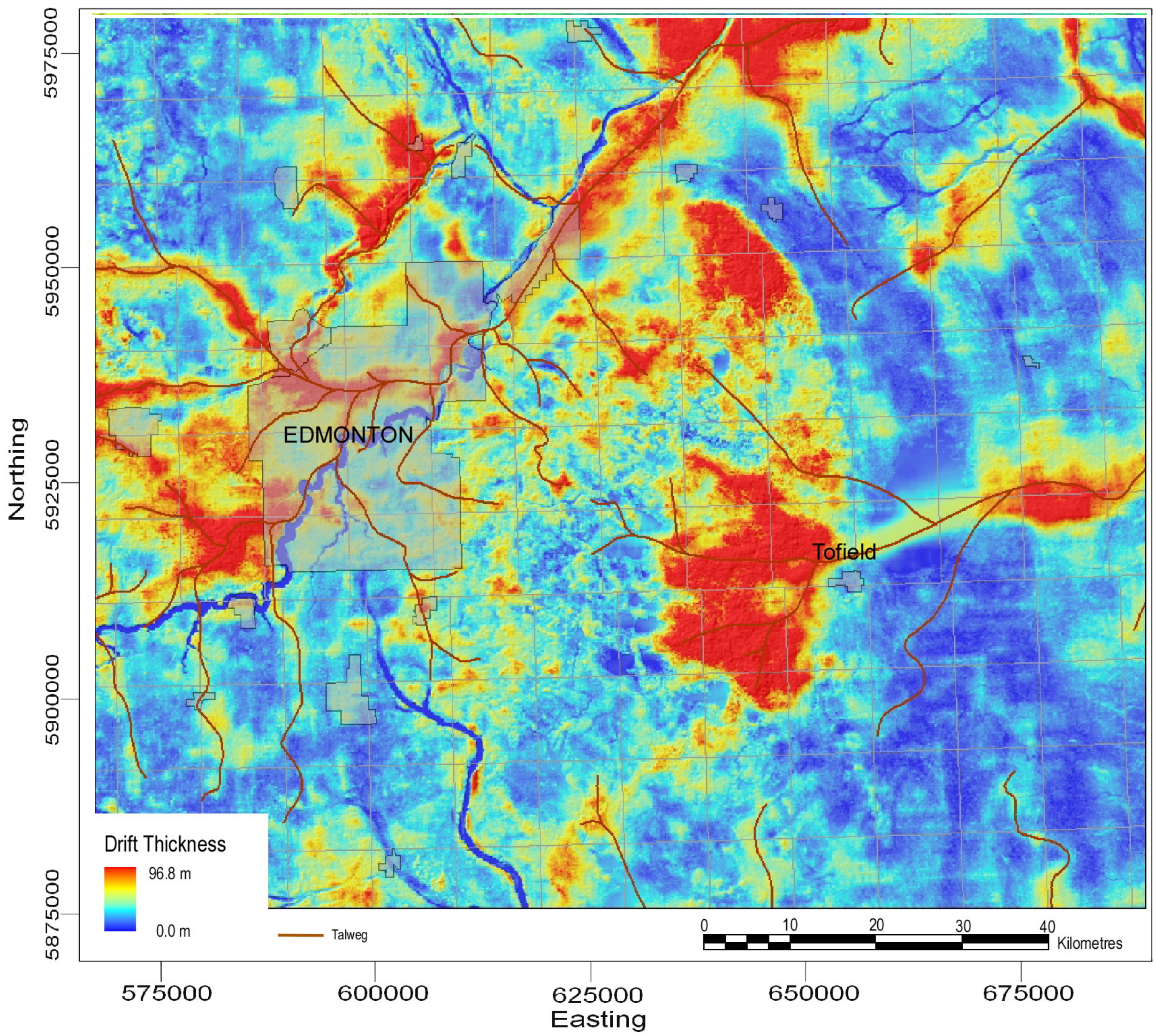


Figure 14. Refined drift thickness in the Edmonton area (NTS 83H).

7 Conclusions

This study confirms our belief that geoscience information, such as surficial geology, bedrock geology, depth to groundwater, depth to bedrock, thermal conductivity, transmissivity and hydraulic conductivity, is valuable in the planning, site characterization, design, installation and operating stages of a geoexchange project. This is particularly the case for instances where small (domestic) installations are being considered, because the cost of drilling a thermal-test borehole would usually render a small installation unfeasible.

Information on the characteristics of the drift deposits appears to be of greater importance than information on the bedrock because the character and thickness of the drift deposits vary to a much greater extent than those of the bedrock formations. In addition, drilling conditions and thermal properties are much less predictable for the drift deposits than for underlying bedrock. Since drilling cost is the most significant financial factor in the execution of a geoexchange project, surficial-geology and drift-deposit isopach maps that can be translated easily into 'drillability' or 'ease-of-drilling' maps can be of great

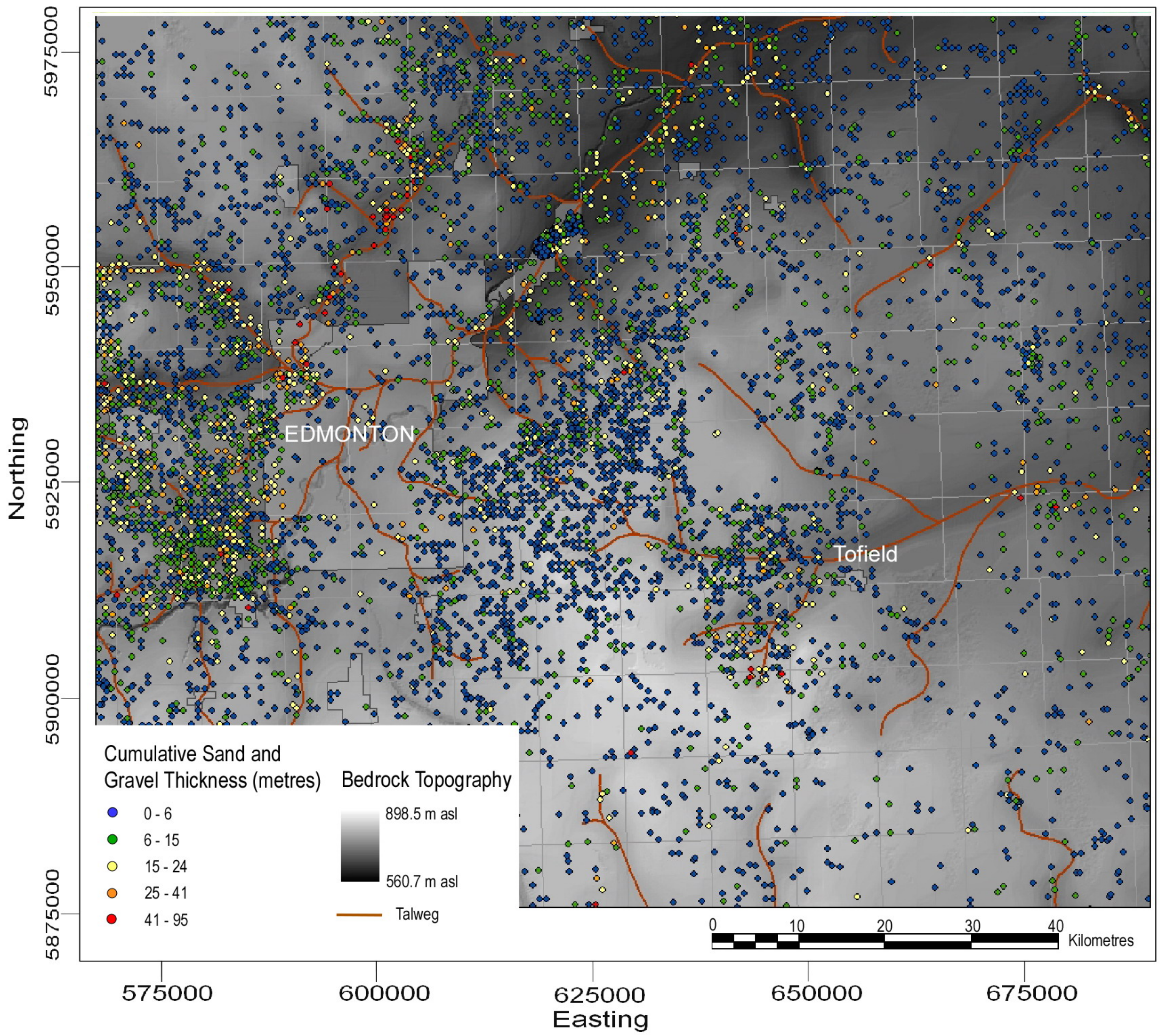


Figure 15. Cumulative sand and gravel thickness at drillhole locations in the Edmonton area (NTS 83H) and the elevation of the bedrock surface, based on lithology data from water-well drillers' logs and lithologs from past AGS drilling projects.

assistance. Open-loop groundwater-coupled geoexchange systems were not discussed in this report. They are rarely considered in Alberta because of regulatory requirements (i.e., require water licence and approval from Alberta Environment). However, better information and knowledge about the occurrence, quality and sustainable supply of Alberta's shallow groundwater would also assist in the appropriate siting and design of open-loop groundwater-coupled geoexchange systems.

Despite the difficulties in obtaining drift-sediment core samples, the drilling and thermal-testing pilot project at the Hastings Lake Community Hall site provided an insight into the local geological and thermal conditions, and highlighted some of the differences between the drift deposits and the bedrock, in terms of drilling difficulty, borehole stability, lithological composition and thermal properties. A better core recovery for the drift sediments may be achievable with a different drilling technique (i.e., vibrosonic or hollow-stem auger with split-spoon system).

Our in-house testing of thermal properties using new equipment was partly successful in that it produced results within the published ranges of thermal conductivities for the water-saturated sediment types tested. A preliminary calculation of the thickness-weighted average thermal conductivity of the deep borehole (HL-08-02) came reasonably close to the thermal conductivity measured in situ with the formation thermal-conductivity (FTC) test. However, the methods for testing core samples of unsaturated sediments and rocks still need to be improved.

The modelling exercise in Section 5 demonstrates that knowledge of the thermal properties of the ground is important because they determine 1) the amount of heat energy that can be extracted, 2) the rate at which it can be extracted, and 3) the extent of the region around the extraction point that will be affected by the operation of the geoexchange system. Other factors, such as design parameters (relative annual balance of heating and cooling loads, ground-loop configuration, heat-pump efficiency, type of borehole grout, individual borehole configuration) and economic parameters (cost of electricity and natural gas, drilling costs, etc.) can have a significant effect on the cost and operation of a geoexchange system. The cost of drilling is the overriding financial factor in the overall cost of a closed-loop vertical-borehole geoexchange system. Reliable geoscience information on the type, composition, thickness and thermal properties of geological materials that need to be penetrated is important to keep drilling costs to a minimum.

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Appendices

Appendix 1 – Samples of Surficial Materials for Analysis of Lithological and Thermal Properties

Sample Number	Easting	Northing	Location Comments	Date	Sample Unit Top (cm)	Sample Unit Bottom (cm)	Lithology	Comments	Munsell[1]
TC-07-1	353450	5925200	Spruce Bend	17-Sep-07	90	105	Brown till	Mapped as Cooking Lake Till; taken near crest of hummock undisturbed area in Parkland bush; sample is dry	2.5Y5/3 red oxidized 5YR6/4
TC-07-2	353450	5925200	Spruce Bend	17-Sep-07	105	120	Brown till	Mapped as Cooking Lake Till; taken near crest of hummock; undisturbed area in Parkland bush; sample is dry; white pebbles; fleck of coal; weathered pink after 2 months	2.5Y5/4 to 5Y5/4 to red oxidized 2.5YR7/4
TC-07-3	353450	5925200	Spruce Bend, another hole	17-Sep-07	119	130.5	Brown till	Mapped as Cooking Lake Till; taken in bottom of trough between hummock crests; undisturbed area in parkland bush; sample is dry; pebbles in sample	2.5Y6/8, 5Y4/1, 5Y8/1
TC-07-4	335090	5927850	Cleared area west of Hwy. 21	17-Sep-07	453	475	Brown till	Mapped as Cooking Lake Till; taken from the bottom of a fresh roadcut for Hwy. 21 twinning; sample would have been at a depth of 4.5 m below top of roadcut; sample is slightly moist	5Y2.5/2 to 5Y3/1
TC-07-5	371350	5930350	Blackfoot Grazing Reserve, Waskehegan Staging Area (north of parking lot)	17-Sep-07	41	52.5	Brown till	Mapped as Cooking Lake Till; taken from a gently rolling hummocky surface in undisturbed parkland bush; sample is moist	10YR3/1, 7.5YR4/6
TC-07-6	371350	5930350	Blackfoot Grazing Reserve, Waskehegan Staging Area (north of parking lot)	17-Sep-07	52.5	64	Brown till	Mapped as Cooking Lake Till; taken from a gently rolling hummocky surface in undisturbed parkland bush; sample is moist	2.5Y3/1

Sample Number	Easting	Northing	Location Comments	Date	Sample Unit Top (cm)	Sample Unit Bottom (cm)	Lithology	Comments	Munsell[1]
TC-07-7	371350	5930350	Blackfoot Grazing Reserve, Waskehegan Staging Area (north of parking lot)	17-Sep-07	64	77	Brown till	Mapped as Cooking Lake Till; taken from a gently rolling hummocky surface in undisturbed parkland bush; sample is moist	GLEY1 3/N, 2.5Y4/4
TC-07-8	371350	5930350	Blackfoot Grazing Reserve, Waskehegan Staging Area (north of parking lot)	17-Sep-07	77	95	Brown till	Mapped as Cooking Lake Till; taken from a gently rolling hummocky surface in undisturbed parkland bush; sample is moist; small fragment of bedrock (siltstone-sandstone)	GLEY1 3/N, 2.5Y4/3
TC-07-9	371350	5930350	Blackfoot Grazing Reserve, Waskehegan Staging Area (north of parking lot)	17-Sep-07	95	110	Brown till	Mapped as Cooking Lake Till; taken from a gently rolling hummocky surface in undisturbed parkland bush; sample is moist	2.5Y4/2
TC-07-10	334108	5921695	Klondike Valley Campground (abandoned); cleared, vegetated with grass	11-Oct-07	50.5	72	Silty clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay	2.5Y3/3
TC-07-11	334108	5921695	Klondike Valley Campground (abandoned); cleared, vegetated with grass	11-Oct-07	72	91	Silty clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay	2.5Y5/1 TO 2.5Y5/3
TC-07-12	334108	5921695	Klondike Valley Campground (abandoned); cleared, vegetated with grass	11-Oct-07	91	110	Silty clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay	2.5Y5/1 with 2.5Y5/6
TC-07-13	334108	5921695	Klondike Valley Campground (abandoned); cleared, vegetated with grass	11-Oct-07	110	132	Silty clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay	2.5Y5/3

Sample Number	Easting	Northing	Location Comments	Date	Sample Unit Top (cm)	Sample Unit Bottom (cm)	Lithology	Comments	Munsell[1]
TC-07-14	317921	5919035	Crown land north of Devon; low–relief, rolling, clear area within aspen stand	11-Oct-07	56.5	75	Sand	Mapped as eolian sand and silt; medium- to fine-grained sand	2.5Y5/6
TC-07-15	317921	5919035	Crown land north of Devon; low–relief, rolling, clear area within aspen stand	11-Oct-07	78.5	100.5	Sand	Mapped as eolian sand and silt; medium- to fine-grained sand	2.5Y5/4
TC-07-16	317921	5919035	Crown land north of Devon; low–relief, rolling, clear area within aspen stand	11-Oct-07	100.5	122.5	Sand	Mapped as eolian sand and silt; medium- to fine-grained sand	2.5Y4/3
TC-07-17	310960	5923343	North of Sand Hills road; on a hill in pine stand	11-Oct-07	23	45	Sand	Mapped as eolian sand and silt; medium- to coarse-grained sand; small pebble (4 mm)	2.5Y5/4
TC-07-18	310960	5923343	North of Sand Hills road; on a hill in pine stand	11-Oct-07	45	70.5	Sand	Mapped as eolian sand and silt; medium- to coarse-grained sand; small pebble (4 mm)	2.5Y4/3 to 2.5Y5/4
TC-07-19	310960	5923343	North of Sand Hills road; on a hill in pine stand	11-Oct-07	70.5	93.5	Sand	Mapped as eolian sand and silt; medium- to coarse-grained sand; small pebble (4 mm)	2.5Y4/4
TC-07-20	310120	5922694	North of oil battery; low-relief, rolling topography.	11-Oct-07	51	76	Sand	Mapped as eolian sand and silt; medium-grained sand	2.5Y4/3
TC-07-21	310120	5922694	North of oil battery; low-relief, rolling topography.	11-Oct-07	76	97	Sand	Mapped as eolian sand and silt; medium-grained sand	2.5y3/2

Sample Number	Easting	Northing	Location Comments	Date	Sample Unit Top (cm)	Sample Unit Bottom (cm)	Lithology	Comments	Munsell[1]
TC-07-22	310120	5922694	North of oil battery; low-relief, rolling topography.	11-Oct-07	97	121	Sand	Mapped as eolian sand and silt; medium-grained sand	2.5y4/4
TC-07-23	311399	5918541	Gramina School; flat grassy area	11-Oct-07	40.5	64	Sand	Mapped as eolian sand and silt; medium- to fine-grained sand	2.5y5/3
TC-07-24	311399	5918541	Gramina School; flat grassy area	11-Oct-07	64	82.5	Sand	Mapped as eolian sand and silt; medium- to fine-grained sand	2.5Y5/3
TC-07-25	326885	5922759	North of 9th Ave., Ellerslie; flat topography	11-Oct-07	26	46.5	Clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay; clay with minor silt; very sticky	2.5Y3/2
TC-07-26	326885	5922759	North of 9th Ave., Ellerslie; flat topography	11-Oct-07	46.5	68.5	Clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay; clay with minor silt; very sticky	2.5Y4/1
TC-07-27	326885	5922759	North of 9th Ave., Ellerslie; flat topography	11-Oct-07	68.5	84.5	Clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay; clay with minor silt; very sticky	2.5Y5/1
TC-07-28	330080	5922657	Cleared pad just west of golf range	11-Oct-07	90.5	97.5	Clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay; very sticky	5Y3/2 some 5Y2.5/1
TC-07-29	330080	5922657	Cleared pad just west of golf range	11-Oct-07	97.5	112	Clay	Mapped as Glacial Lake Edmonton lacustrine silt and clay; very sticky	5Y4/2 some 5Y2.5/1 with white (5y8/1)

[1] Munsell colours were determined in dry conditions under fluorescent lighting.

Appendix 2 – Lithological Description of Quaternary and Bedrock Sections of Borehole HL-08-01, Based on Driller's Log, Drillcore Samples and Geophysical Logs from Borehole HL-08-02

Depth from (m)	Depth to (m)	Thickness (m)	Primary Lithology	Secondary Lithology	Comments
0.00	0.69	0.69	Silt	sandy	fine sandy silt till, no reaction with HCl, 10YR3/2; ~2–5% clast content, angular to subangular granules to pebbles, occasional subangular cobbles; clasts include granite, quartzite and coal
0.69	1.08	0.39	Silt		silt till, 10YR3/1; ~2% clast content, dominantly granules of quartzite and occasional subangular granite pebbles, less coal visible, no reaction with HCl
1.27	2.44	1.17	Silt	clayey	clayey silt till, 2.5Y3/1; <2% clast content, subangular granite granules to pebbles, and subangular quartzite pebbles, coal visible, no reaction with HCl
2.44	2.87	0.43	Silt	sandy	fine sandy silt till, 2.5Y4/2, no reaction with HCl; contains 2–5% clasts including subangular granite and quartzite granules to pebbles, as well as limestone pebbles
2.87	5.80	2.93	No recovery		
5.80	6.00	0.20	Clay	silty	silty clay till, 10YR3/1, no reaction with HCl, massive; <2% clast content with rare granules, single facetted quartzite pebble
6.00	10.50	4.50	No recovery		
10.50	10.70	0.20	Sand	silty	silty sand till, 2.5Y3/3, no reaction with HCl; ~2% clast content, subrounded quartzite granules and two quartzite cobbles
10.70	22.40	11.70	No recovery		
22.40	22.70	0.30	Silt	sandy	sandy silt till, 10YR3/1, strong HCl reaction; ~2–5% clast content, limestone pebbles, angular to subangular quartz granules to small pebbles, no pink granite or coal observed, but plagioclase-rich granite pebbles (subrounded), hydrocarbon odour
22.70	25.50	2.80	No recovery		
25.50	25.58	0.08	Gravel		fractured limestone cobble and subrounded quartzite cobble

Depth from (m)	Depth to (m)	Thickness (m)	Primary Lithology	Secondary Lithology	Comments
25.58	25.80	0.22	Silt	sandy	sandy silt till, 10YR3/1, strong HCl reaction, ~2-5% clast content, limestone pebbles, angular - subangular quartz granules - small pebbles, pink granite pebbles, hydrocarbon odour
25.80	25.87	0.07	Silt	sandy	fine sandy silt till, 10YR3/2, moderate HCl reaction; fewer clasts present, but recovery is poor, granules more abundant, with few pebbles observed
25.87	39.40	13.53	No recovery		
39.40	39.54	0.14	Silt	sandy	fine sandy silt till, 2.5Y1/1, moderate to slight HCl reaction; rounded limestone pebbles, subrounded orthoclase granite pebbles, subrounded to subangular quartzite pebbles, some coal fragments, no hydrocarbon odour
39.54	42.36	2.82	No recovery		
42.36	43.43	1.07	Sandstone	argillaceous	very fine to fine sandstone; weathered
43.43	44.35	0.91	Shale		fractured weathered shale
44.35	44.50	0.15	Sandstone	argillaceous	very fine to fine sandstone
44.50	44.96	0.46	Shale	bentonitic	weathered shale; clayey
44.96	45.42	0.46	Shale	silty	wavy banded, silty shale, coaly towards base
45.42	45.72	0.30	Coal		fractured coal
45.72	46.33	0.61	Shale	bentonitic	very clayey shale
46.33	47.40	1.07	Coal		highly fractured
47.40	47.85	0.46	Shale		probably shale (not recovered)
47.85	48.77	0.91	Coal		poor recovery
48.77	50.60	1.83	Shale	silty	wavy shale, fractured at top; then wavy banded shale/silt
50.60	50.90	0.30	Coal		
50.90	52.12	1.22	Bentonite		no recovery; inferred from borehole HL-08-02

Appendix 3. Lithology Description of Quaternary and Bedrock Sections of HL-08-02, Based on Driller's Log, Drillcore Samples and Geophysical Logs

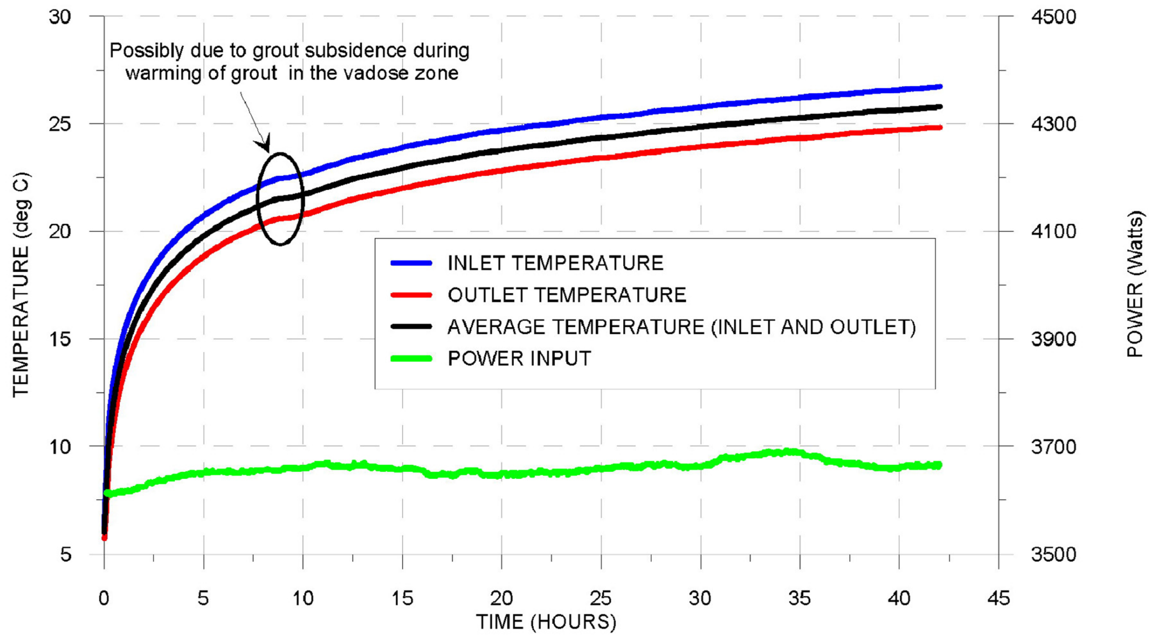
Depth from (m)	Depth to (m)	Thickness (m)	Primary Lithology	Secondary Lithology	Comments
0.00	3.10	3.10	Silt	clay	clay/till
3.10	4.90	1.80	Silt	sandy	sandy silt
4.90	5.10	0.20	Silt	gravelly	gravelly/cobbly silt
5.10	10.10	5.00	Silt	sandy	sandy silt
10.10	13.70	3.60	Silt	gravelly	gravelly/cobbly silt
13.70	21.00	7.30	Silt	sandy	sandy silt
21.00	22.00	1.00	Silt	clay	clay/till
22.00	24.40	2.40	Silt	sandy	sandy silt
24.40	30.20	5.80	Clay	silt	silty clay
30.20	42.40	12.20	Silt	sandy	sandy silt
42.40	45.72	3.32	Shale		
45.72	46.20	0.48	Shale		fractured, weathered shale, brownish grey
46.20	47.25	1.05	Coal		banded (dull and bright) banded coal
47.25	48.00	0.75	Shale		
48.00	48.95	0.95	Coal		
48.95	50.40	1.45	Shale	silty	medium-grey silty shale
50.40	50.80	0.40	Coal		
50.80	51.20	0.40	Bentonite		
51.20	51.97	0.77	Bentonite		no recovery (inferred)
51.97	52.40	0.43	Shale	silty	medium-grey silty shale
52.40	53.00	0.60	Siltstone		
53.00	53.65	0.65	Shale		fractured shale, dark brown to black (small coaly bits)
53.65	54.00	0.35	Sandstone		light grey sandstone with thin brownish wavy laminae
54.00	54.60	0.60	Siltstone	argillaceous	wavy-laminated argillaceous siltstone/shale, coarsening upward
54.60	58.20	3.60	Shale	silty	medium-brown silty shale with coaly bits
58.20	59.70	1.50	Sandstone		light grey arkosic sandstone

Depth from (m)	Depth to (m)	Thickness (m)	Primary Lithology	Secondary Lithology	Comments
59.70	60.30	0.60	Shale		
60.30	60.90	0.60	Sandstone		
60.90	62.80	1.90	Siltstone	argillaceous	argillaceous siltstone to silty shale, fracture zone between 60.9 and 61.2 m; pebble-sized ironstone clasts (0.5–1.5 cm) at 61.5 and 62.5 m
62.80	63.60	0.80	Shale	silty	fractured, medium grey, silty shale to argillaceous siltstone
63.60	64.20	0.60	Coal		
64.20	65.70	1.50	Siltstone		argillaceous siltstone to sandstone, laminated and crossbedded
65.70	67.80	2.10	Sandstone		light grey arkosic sandstone, fluvial only at about 67 m
67.80	69.20	1.40	Siltstone		fining-upward sandstone to siltstone, some shale with ironstone pebble lags
69.20	69.80	0.60	Sandstone		light grey, argillaceous sandstone, very fine grained
69.80	70.10	0.30	Shale	silty	silty shale
70.10	74.60	4.50	Sandstone	silty	wavy-laminated silty sandstone/siltstone, coarsening upward
74.60	75.10	0.50	Coal		bright coal
75.10	75.60	0.50	Shale		
75.60	77.40	1.80	Coal		bright coal
77.40	78.90	1.50	Shale	silty	medium grey silty shale, fractured, with rootlets at contact with coal(?)
78.90	80.30	1.40	Sandstone		light grey arkosic sandstone
80.30	81.00	0.70	Siltstone	argillaceous	argillaceous siltstone
81.00	81.50	0.50	Sandstone		
81.50	82.00	0.50	Siltstone	argillaceous	argillaceous siltstone
82.00	83.00	1.00	Sandstone	argillaceous	dark grey, argillaceous, very fine sandstone
83.00	83.30	0.30	Shale	silty	silty shale
83.30	84.20	0.90	Sandstone	argillaceous	brown, very fine argillaceous sandstone with coaly bits, ironstone pebbles at 84 m
84.20	84.80	0.60	Shale	silty	silty shale
84.80	85.60	0.80	Sandstone		light grey arkosic sandstone

Depth from (m)	Depth to (m)	Thickness (m)	Primary Lithology	Secondary Lithology	Comments
85.60	85.90	0.30	Siltstone		dark grey siltstone
85.90	86.00	0.10	Bentonite		
86.00	86.30	0.30	Siltstone		
86.30	86.40	0.10	Bentonite		
86.40	86.60	0.20	Siltstone		coaly siltstone/shale
86.60	86.65	0.05	Coal		bright coal
86.65	87.20	0.55	Siltstone		coaly shale/siltstone
87.20	90.60	3.40	Shale	silty	brown, coaly, silty shale/siltstone; no recovery from 87.4 to 90 m (inferred)
90.60	91.90	1.30	Sandstone		light grey bentonitic arkosic sandstone
91.90	94.00	2.10	Shale	silty	laminated dark brown silty shale with silt interbeds
94.00	94.30	0.30	Bentonite		
94.30	96.40	2.10	Shale	silty	wavy-laminated silty shale with sandstone interbeds (<10 cm); 1 cm ironstone layer at 96.25 m
96.40	96.60	0.20	Sandstone		light grey bentonitic arkosic sandstone, with black wavy laminae
96.60	97.50	0.90	Shale	silty	dark grey-brown silty shale
97.50	98.80	1.30	Sandstone		light grey arkosic sandstone, rusty, hard ironstone layer (5 cm) at 98.15 m
98.80	101.60	2.80	Siltstone	argillaceous	wavy-laminated, dark grey-brown argillaceous siltstone and shale; ironstone layers (5 cm) at 99.4 and 100.56 m, possibly sandstone layer at 101 m (not recovered)
101.60	102.40	0.80	Coal		
102.40	104.20	1.80	Shale	silty	dark grey-brown silty shale, decreasing silt, increasing organic material (black) towards top
104.20	110.20	6.00	Sandstone	argillaceous	flaser-bedded, wavy-laminated, grey/black argillaceous sandstone/siltstone/shale interbeds, bioturbated in places, high organic material content (coal flakes); bay environment
110.20	111.10	0.90	Coal		some coal-rich shale layers (could be dull coal/charcoal/fusinite)
111.10	112.10	1.00	Shale	silty	black/grey silty-sandy, bentonitic shale, lenticular silt/sand interlayers, increasing

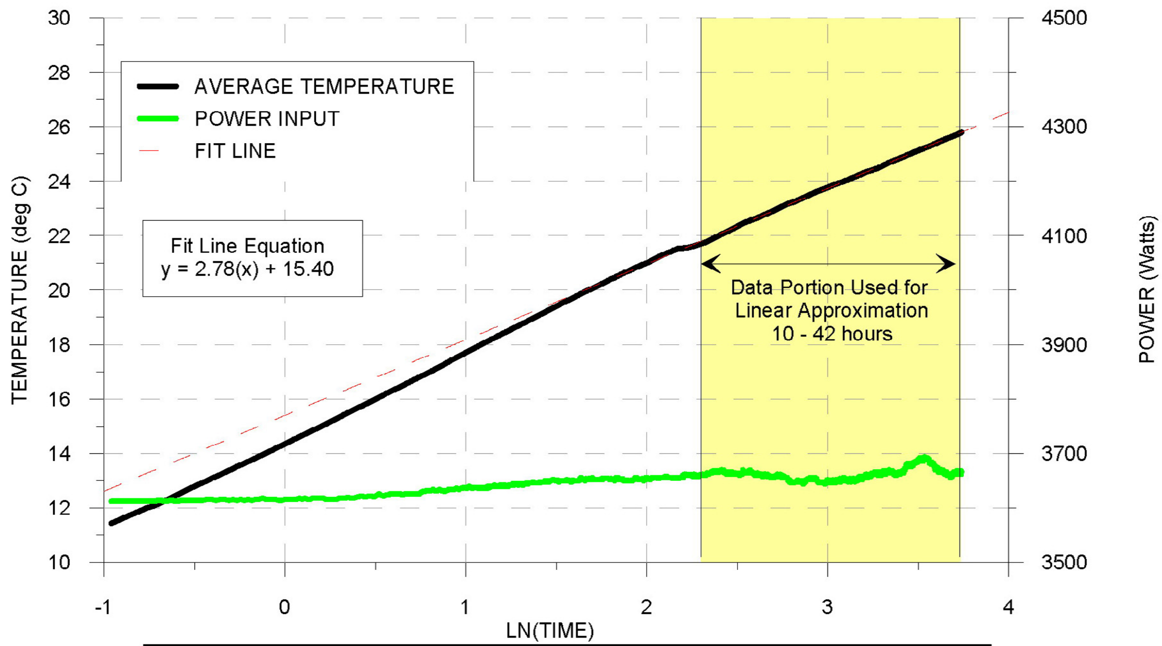
Depth from (m)	Depth to (m)	Thickness (m)	Primary Lithology	Secondary Lithology	Comments
					bentonite upwards
112.10	112.40	0.30	Coal		bright coal
112.40	113.20	0.80	Shale	silty	silty shale grading upward into medium grey siltstone, fractured with brown alteration along factures (rootlets from overlying vegetation, coal)
113.20	113.80	0.60	Sandstone		light grey arkosic sandstone with coaly bits
113.80	115.20	1.40	Shale	silty	dark grey-brown silty shale, ironstone at 115 m
115.20	115.80	0.60	Sandstone		medium grey, laminated, fine-grained sandstone; channel
115.80	118.70	2.90	Sandstone		interbedded, wavy–laminated, arkosic sandstone/siltstone; ironstone layer at 117.5 m; pond
118.70	119.20	0.50	Coal		bright; with rootlets and plant matter
119.20	120.00	0.80	Shale	silty	dark grey-brown silty shale; carbonaceous
120.00	120.90	0.90	Sandstone		light grey, fine arkosic sandstone
120.90	121.10	0.20	Siltstone	argillaceous	dark brown/grey (argillaceous siltstone) shale/siltstone interlamination; estuarine sequence
121.10	122.00	0.90	Siltstone	argillaceous	medium grey/brown argillaceous siltstone with shale laminae
122.00	122.83	0.83	Shale	silty	silty shale

Appendix 4 – Formation Thermal Conductivity (FTC) Test Data and Results, Borehole HL08-01



Borehole Data (See Figure 6 for Borehole Details)		
Borehole Depth	52.1 m	171 ft
Borehole Diameter	139.7 mm	5.5 in
Undisturbed Soil Temperature	6.1 deg C	43.0 deg F
U-Tube Size	25.4 mm	1 in
U-Tube Depth	52.1 m	171 ft
Grout Type	Baroid Quik Grout	
Grout Mix	20% Bentonite Solids	

Test Data	
Test Start	March 3, 2008 19:46
Test Duration	42 hours
Average Power	3659 W
Average Power per bore m	70.23 W/m
Average Heat Input	12494 Btu/hr
Average Heat Input per bore ft	73.06 Btu/hr-ft



Line Source Results	
Fit Line Slope	2.78
Average Heat Input per bore ft	73.06 Btu/hr-ft
Average Power per bore m	70.23 W/m
Thermal Conductivity	2.01 W/m-K
Thermal Conductivity	1.16 Btu/hr-ft -°F
Soil Volumetric Heat Capacity[1]	32.4 Btu/ft^3-°F
Thermal Diffusivity	0.86 ft^2/day
Thermal Diffusivity	0.080 m^2/day

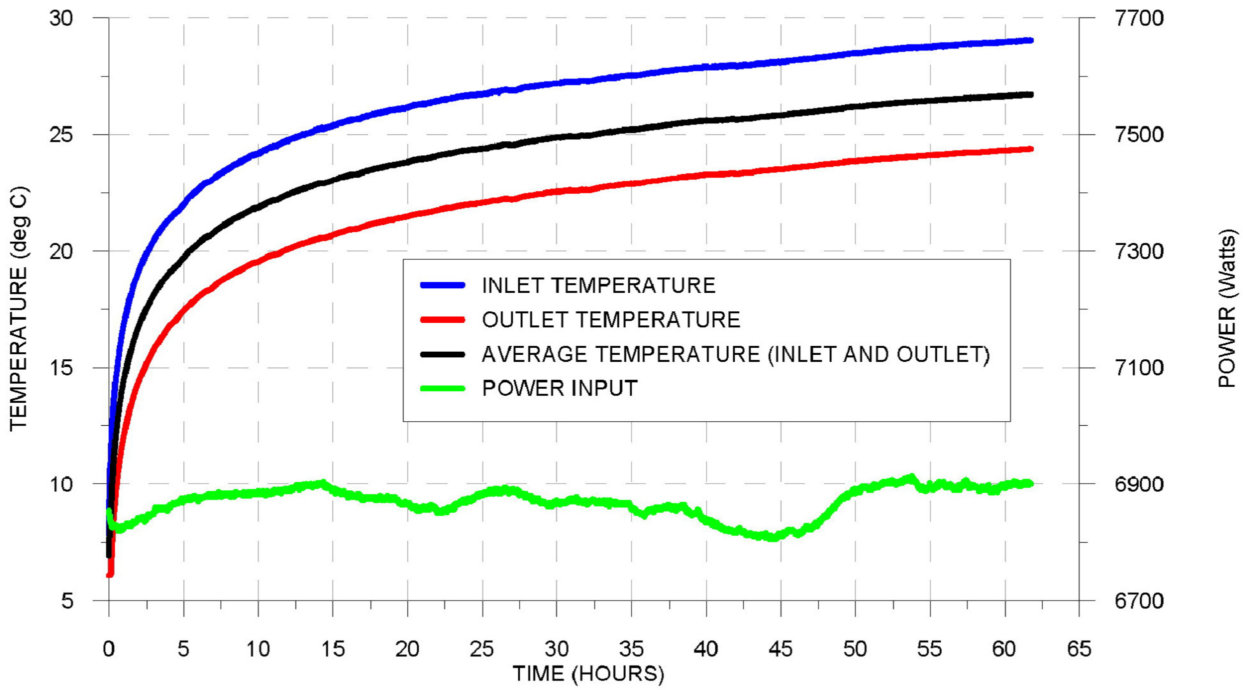
Cylindrical Source Results [2]	
Thermal Conductivity	1.81 W/m-°K
Thermal Conductivity	1.05 Btu/hr-ft -°F
Borehole Resistance	0.1266 m -K/W
Borehole Resistance	0.2191 hr-ft-°F/Btu

NOTES:

[1] Weighted average for borehole material based on typical values provided in Kavanaugh and Rafferty (1997).

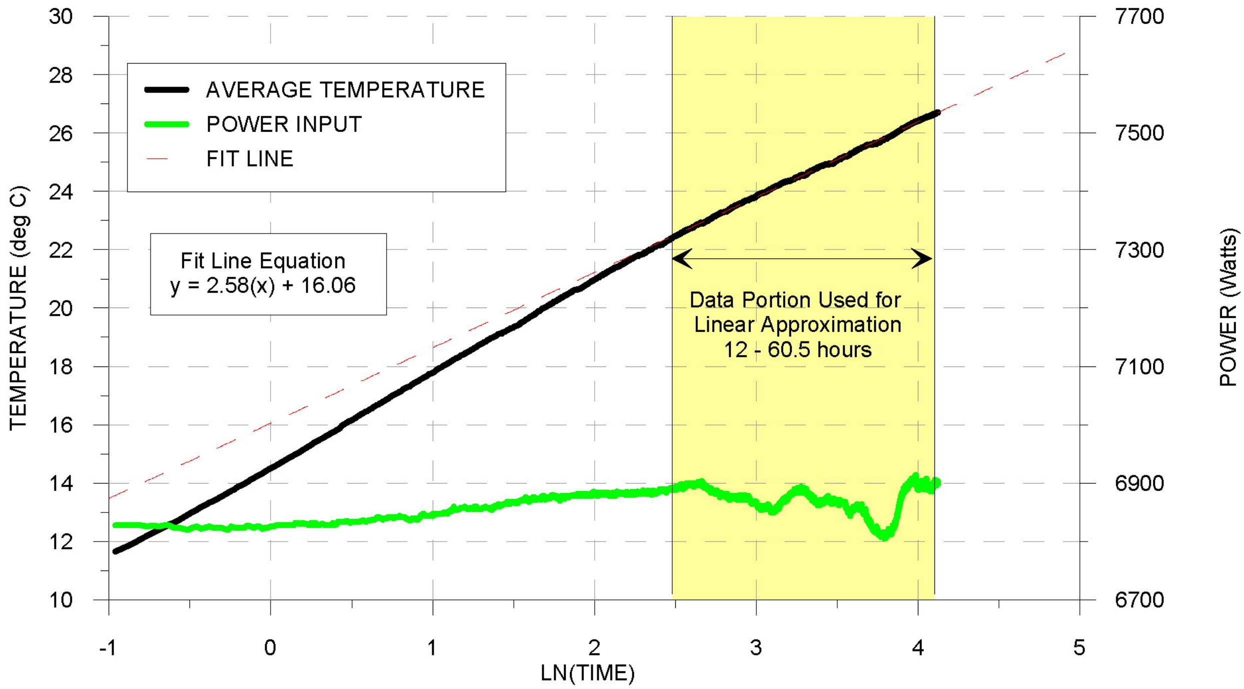
[2] Output from numerical analysis using Geothermal Properties Measurements v 1.1 (Shonder and Beck, 2000).

Appendix 5 – Formation Thermal Conductivity (FTC) Test Data and Results, Borehole HL08-02



Borehole Data (See Figure 6 for Borehole Details)		
Borehole Depth	122.8 m	403 ft
Borehole Diameter	139.7 - 200mm	5.5 – 7.875 in
Undisturbed Soil Temperature	6.8 deg C	44.2 deg F
U-Tube Size	25.4 mm	1 in
U-Tube Depth	121.9 m	400 ft
Grout Type	Baroid Quik Grout	
Grout Mix	20% Bentonite Solids	

Test Data	
Test Start	March 5, 2008 16:43
Test Duration	60.5 hours
Average Power	6868 W
Average Power per bore m	56.34 W/m
Average Heat Input	23454 Btu/hr
Average Heat Input per bore ft	58.1 Btu/hr-ft



Linear Regression Results	
Fit Line Slope	2.58
Average Heat Input per bore ft	58.1 Btu/hr-ft
Average Power per bore m	56.34 W/m
Thermal Conductivity	1.74 W/m-K
Thermal Conductivity	1.01 Btu/hr-ft -°F
Soil Volumetric Heat Capacity[1]	31.4 Btu/ft^3-°F
Thermal Diffusivity	0.77 ft^2/day
Thermal Diffusivity	0.072 m^2/day

Numerical Analysis Results [2]	
Thermal Conductivity	1.59 W/m-K
Thermal Conductivity	0.92 Btu/hr-ft -°F
Borehole Resistance	0.1851 (m-K/W)
Borehole Resistance	0.3203 (hr-ft-°F/Btu)

NOTES:

[1] Weighted average for borehole material based on typical values provided in Kavanaugh and Rafferty (1997).

[2] Output from numerical analysis using Geothermal Properties Measurements v 1.1 (Shonder and Beck, 2000).

Appendix 6 – Thermal Conductivity Testing Results for Core Samples from Boreholes HL-08-01 and HL-08-02, Hastings Lake Community Hall Pilot-Study Site

Borehole	Depth (m)	Lithology	Secondary Lithology	Thermal Conductivity (W/m.K)
HL-08-01	0.30	Silt	sandy silt in clay matrix	1.76
HL-08-01	0.82	Silt	silt in clay matrix, till	2.52
HL-08-01	1.20	Silt	silt in clay matrix	2.17
HL-08-01	2.71	Silt	fine sandy silt in clay matrix, till	2.30
HL-08-01	5.90	Clay	silty clay, till	2.21
HL-08-01	10.55	Sand	silty sand, till	2.52
HL-08-01	22.60	Silt	sandy silt in clay matrix, till	3.17
HL-08-01	25.70	Silt	sandy silt in clay matrix, till	2.86
HL-08-01	39.50	Silt	fine sandy silt in clay matrix, till	2.24
HL-08-01	45.70	Shale	dark brown/black coaly shale/siltstone	1.66
HL-08-01	49.60	Shale	medium grey shale with fracture	1.57
HL-08-02	46.00	Shale	fractured, weathered shale, brownish grey	2.01
HL-08-02	46.20	Coal		0.79
HL-08-02	48.00	Coal		0.77
HL-08-02	49.30	Shale	fractured shale, brown/grey (small coaly bits)	1.50
HL-08-02	50.20	Shale	medium grey shale, silty(?)	2.15
HL-08-02	51.00	Shale	shale breccia, grey shale clasts in light grey–weathered matrix	1.96
HL-08-02	52.25	Shale	medium grey shale, silty(?)	2.07
HL-08-02	52.80	Siltstone	siltstone	2.31
HL-08-02	53.20	Shale	fractured shale, dark brown to black (small coaly bits)	1.90
HL-08-02	53.65	Sandstone	light grey sandstone with thin brownish wavy laminae	1.94
HL-08-02	53.70	Shale	medium brown silty shale with coaly bits	1.55
HL-08-02	56.40	Shale	medium brown silty shale with coaly bits	1.87
HL-08-02	58.00	Sandstone	light grey arkosic sandstone	2.22
HL-08-02	59.50	Sandstone	light grey arkosic sandstone	2.27
HL-08-02	61.25	Shale	medium brown silty shale	2.18
HL-08-02	63.00	Siltstone	fractured, medium grey argillaceous siltstone	2.02

Borehole	Depth (m)	Lithology	Secondary Lithology	Thermal Conductivity (W/m.K)
HL-08-02	63.70	Coal		0.65
HL-08-02	65.00	Sandstone	light grey, argillaceous, arkosic sandstone, fine grained, with thin wavy laminae	2.55
HL-08-02	66.80	Sandstone	light grey arkosic sandstone	2.35
HL-08-02	68.30	Sandstone	light grey arkosic sandstone	2.35
HL-08-02	69.70	Sandstone	light grey argillaceous sandstone, very fine grained	2.22
HL-08-02	71.20	Sandstone	light grey arkosic sandstone	2.39
HL-08-02	74.00	Sandstone/ siltstone	interbedded siltstone/sandstone	2.17
HL-08-02	76.50	Coal		0.67
HL-08-02	77.80	Shale	medium-grey silty shale, fractured, with rootlets(?)	2.00
HL-08-02	79.50	Sandstone	light grey arkosic sandstone	2.20
HL-08-02	80.85	Siltstone	shale breccia, grey shale clasts in brownish silt matrix	2.17
HL-08-02	82.00	Sandstone	dark grey, argillaceous, very fine sandstone	2.03
HL-08-02	83.80	Sandstone	brown, very fine sandstone with coaly bits	1.84
HL-08-02	84.90	Sandstone	light grey arkosic sandstone	2.15
HL-08-02	85.60	Siltstone	dark grey siltstone	2.26
HL-08-02	85.90	Bentonite	light grey bentonite with hairline fractures	2.00
HL-08-02	86.30	Bentonite	light grey bentonite with hairline fractures	1.92
HL-08-02	86.60	Coal		0.99
HL-08-02	87.20	Shale	medium-brown silty shale with coaly bits	1.83
HL-08-02	91.80	Sandstone	light grey bentonitic arkosic sandstone	1.92
HL-08-02	92.80	Shale	dark grey-brown silty shale	2.29
HL-08-02	94.20	Bentonite	light grey bentonite, cut along bedding	1.94
HL-08-02	94.20	Bentonite	light grey bentonite, cut perpendicular to bedding	1.97
HL-08-02	95.10	Shale	dark grey-brown silty shale	2.28
HL-08-02	96.50	Sandstone	light grey bentonitic arkosic sandstone, with black wavy laminae	1.79
HL-08-02	97.30	Shale	dark grey-brown silty shale	2.35
HL-08-02	98.10	Sandstone	light grey arkosic sandstone	2.15
HL-08-02	99.30	Sandstone	light grey arkosic sandstone with silt and shale laminae	2.05
HL-08-02	100.70	Shale	dark grey-brown silty shale	2.25

Borehole	Depth (m)	Lithology	Secondary Lithology	Thermal Conductivity (W/m.K)
HL-08-02	102.00	Coal		0.66
HL-08-02	103.50	Shale	dark grey-brown silty shale	2.17
HL-08-02	105.00	Sandstone	grey/brown, wavy-laminated sandstone/siltstone	2.28
HL-08-02	107.30	Sandstone	grey/black, wavy–laminated, arkosic sandstone, high organics	1.96
HL-08-02	109.00	Sandstone	grey/black, wavy–laminated, arkosic sandstone, high organics	1.86
HL-08-02	110.00	Shale	black/grey silty-sandy shale, lenticular silt/sand interlayers	2.14
HL-08-02	110.50	Shale	dark brown/black shale, high organic content	1.82
HL-08-02	111.50	Shale	black/grey silty-sandy shale, lenticular silt/sand interlayers	2.20
HL-08-02	112.20	Coal		0.67
HL-08-02	113.50	Sandstone	light grey arkosic sandstone with coaly bits	1.91
HL-08-02	115.00	Shale	dark grey-brown silty shale	2.17
HL-08-02	115.40	Sandstone	medium-grey fine sandstone, laminated	2.23
HL-08-02	115.40	Sandstone	light grey arkosic sandstone	2.17
HL-08-02	117.50	Sandstone	medium grey-brown very fine sandstone/ironstone layer	2.73
HL-08-02	118.90	Coal		0.63
HL-08-02	119.30	Shale	dark grey-brown silty shale	1.91
HL-08-02	120.10	Sandstone	light grey, fine arkosic sandstone	1.99
HL-08-02	121.00	Siltstone	dark brown/grey shale/siltstone interlamination	2.36
HL-08-02	121.50	Siltstone	medium-grey/brown siltstone with shale interlaminae	2.65