Evaluating the geothermal heat pump potential from a thermostratigraphic assessment of rock samples in the St. Lawrence Lowlands, Canada

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Abstract

The installation cost and the performance of geothermal heat pump systems are influenced by the thermal state and properties of the subsurface. The ground ability to transfer heat described by thermal conductivity is a dominant factor affecting the favorability of closed-loop ground heat exchangers installed in vertical boreholes. A study that aimed at evaluating the geothermal heat pump potential by mapping the thermal conductivity of rock sequences was, therefore, performed for the St. Lawrence Lowlands sedimentary basin in Canada. Thermal conductivity was measured in the laboratory on rock samples collected in outcrops and used to complete design calculations of a geothermal system with a single borehole. Results allowed the definition of thermostratigraphic units that can be linked to depositional environments. Basal quartz-rich sandstones formed in a rift environment show a high geothermal potential. Overlying dolomites, argillaceous limestones and shales deposited in a passive margin evolving to a foreland basin exhibit a transition toward the top from high to low geothermal potential. Upper turbidites and molasses have a moderate geothermal potential. The thermal conductivity of the thermostratigraphic units is dominantly influenced by the mineralogy of the sedimentary rocks. Understanding their origin is a key to improve geothermal resource assessment and system design to anticipate new installations in the area.

Key Words: geothermal, heat pump, thermostratigraphy, thermal conductivity, sedimentary basin, St. Lawrence Lowlands, Canada.

1 Introduction

Geothermal heat pump systems, also named ground source heat pumps, are one of the most energy efficient alternatives for heating and cooling buildings (Self et al. 2013). This technology relies on the Earth acting as a heat source or sink to maintain building temperatures. The economic viability of vertical systems, where the heat pump is linked to closed-loop ground heat exchangers (GHEs) installed in boreholes, can be affected by the thermal state and properties of the subsurface. In this context, space heating and cooling are influenced by the ground conditions that can be better understand to improve this human activity. In fact, the length of ground heat exchanger required to fulfill the building energy needs is commonly computed with a sizing equation taking into account the subsurface temperature, heat capacity and thermal conductivity (Bernier 2000). Simulating the system operating temperature to evaluate its performance and energy savings also relies on those three parameters (Bernier 2001). The amount and the capacity of tools available to size and simulate the operation of geothermal systems have increased over the past decade. The recent development of analytical and numerical approaches to simulate ground coupled heat pump systems documented in numerous studies outlines the growing interest in this field (Al-Khoury et al. 2005; Al-Khoury and Bonnier 2006; Lamarche and Beauchamp 2007a; Lamarche and Beauchamp 2007b; Cui et al. 2008; Lee and Lam 2008; Lamarche 2009; Li and Zheng 2009; Philippe et al. 2009; Yang et al. 2010; Li et al. 2015; Wang et al. 2015).

Regardless of the approach used, it is critical to supply models with reliable subsurface parameters. Temperature of the shallow subsurface can be found throughout the scientific literature and databases, with data originating from boreholes (Majorowicz et al. 2009) or inferred from the meteorological record (Signorelli and Kohl 2004). In the case of large geothermal heat pump systems, where local variations in subsurface temperature may impact the system design, the subsurface temperature can be measured in a pilot GHE (Gehlin and Nordell 2003).

Estimation of the subsurface volumetric heat capacity is also straightforward as this parameter is relatively uniform within different rock types for the temperature and pressure conditions expected in the shallow subsurface (Clauser 2014a). The sensitivity of geothermal system simulation models with respect to heat storage is additionally less important than that of conductive heat transfer, allowing the toleration of an uncertainty in the evaluation of the subsurface volumetric heat capacity. Appropriate estimation of this parameter can be obtained knowing the dominant mineral phases of the rock formations or with a geological description of the rock type to classify the subsurface heat storage potential (Waples and Waples 2004a, b).

The evaluation of the subsurface thermal conductivity can be more challenging because this parameter varies significantly among rock types, typically on a scale of 0.5 to 8 W m^{-1} K^{-1} at the temperature and pressure conditions of the shallow subsurface (Clauser 2014b). The porosity, water content and the mineral phases, which can be highly heterogeneous, are the main factors affecting the subsurface thermal conductivity (Clauser and Huenges 1995; Clauser 2006). Sedimentary rocks, which are of interest to this research, can have a low thermal conductivity in the range of 0.5 to 2 W m^{-1} K^{-1} when having a marine origin, while sedimentary rocks of terrestrial and chemical origins most commonly have a moderate thermal conductivity between 2 to 4 W m^{-1} K^{-1} (Clauser 2014b). A high thermal conductivity above 4 W m^{-1} K^{-1} is associated to quartz-rich specimens. Thermal response tests have been proposed to assess the subsurface thermal conductivity in a pilot GHE before designing a system (Rainieri et al. 2011; Raymond et al. 2011; Spitler and Gehlin 2015). The test has grown in popularity for designing large ground-coupled heat pump systems, but can remain uneconomical for smaller systems where the test cost is above the economic uncertainty related to an unknown subsurface (Robert and Gosselin 2014). The need to map the distribution of the subsurface thermal conductivity to help design smaller systems or for screening simulations of larger systems is growing with increasing installations of GHEs. For example, regional mapping of the subsurface thermal conductivity has been undertaken in southern Italy, providing field data to guide geothermal designers (Di Sipio et al. 2014). A methodology was then developed to estimate the geothermal potential in this region of Italy based on geological information and simulation of geothermal heat pump systems (Galgaro et al. 2015). Similar attempts to map the geothermal heat pump potential were conducted (Casasso and Sethi 2016; De Filippis et al. 2015; Ondreka et al. 2007; Santilano et al. 2015; Teza et al. 2015) but mostly rely on inferred subsurface thermal conductivity defined with calculations constrained from geological information. In these studies, the geothermal potential is commonly tied to the subsurface thermal conductivity, highlighting the need to collect reliable field data to better assess this property among geological units. Populated regions with expected system installations are priorities for further case studies.

An assessment of the subsurface thermal conductivity in the St. Lawrence Lowlands (SLL) located in the province of Quebec, Canada, is presented in this study. The objective was to evaluate the geothermal heat pump potential of the rock units of this sedimentary basin from laboratory measurements of thermal conductivity. The geothermal potential was evaluated with respect to ground-coupled heat pump systems where the heat exchangers are closed-loops installed in boreholes, which are the most common geothermal systems in the SLL. This potential was therefore linked to the length of borehole needed for a given system to be installed in the area, which is mostly affected by the thermal conductivity of the host rock when comparing similar building loads or energy demand. The information presented provides the basis for a first assessment of the subsurface thermal conductivity at a regional scale in the SLL. The collected data set, submitted as a supplementary material, is believed to be an original contribution that can facilitate geothermal system design based on a thermostratigraphic classification of rock units. The concept of thermostratigraphy is further discussed in the context of geothermal heat pump systems.

2 Geological settings

The SLL forms a sedimentary basin covering ~20 000 km^2 to the south of Quebec province (Figure 1). The region studied includes major cities such as Montreal and Quebec City and has the highest population density in the province. The type of geothermal heat pump system that is most commonly installed in the area is vertical closed-loops (Canadian GeoExchange Coalition 2012).

The sedimentary basin of the SLL is located between the Precambrian basement of the Grenville geological province and the Appalachians. The Precambrian basement is constituted of metamorphosed igneous rocks dominated by gneisses with other igneous and metamorphic rocks (Globensky 1987). Cambrian-Ordovician rocks of the Appalachian mountain belt are mostly sedimentary in origin and have experienced a highly variable degree of metamorphism and deformation.

The Cambrian-Ordovician rocks of the SLL basin formed in a geodynamic context evolving from a rift to a passive margin and a foreland basin (Figure 2; Comeau et al. 2012). The rock strata are relatively non-deformed and well preserved. A large synclinal elongated in the Southwest-Northeast direction is the main structure associated to the SSL basin (Figure 3). Steeply southeast dipping normal faults with a southwest-northeast direction affect the sedimentary sequences, deepening and thickening towards the southeast (Castonguay et al. 2010). Logan’s Line, a major thrust fault zone, delineates the southeastern boundary of the SLL basin, which extends under the Appalachians (Figure 3).

Depositional environments influenced the formation of the sedimentary groups in the SLL basin having distinct mineralogical phases and porosity values, from clay to quartz rich with low to moderate porosity, where changes in rock type are expected to affect the geothermal potential. The basal sandstone of the Potsdam Group unconformably overlies the crystalline basement outcropping at surface toward the Northwest of the SLL basin. This group encloses the Covey Hill Formation of fluviatile origin, constituted of 80 to 98 % quartz and 3 to 10 % plagioclase, as well as the homogenous Cairnside Formation deposited in a shallow subtidal marine to marine deltaic environment and containing more than 98 % quartz (Globensky 1987). The average porosity of the Potsdam Group is between 4 to 6 % and values can locally exceed 10 % (Tran Ngoc et al. 2014), which can affect its geothermal potential.

The Potsdam Group is overlain by the Beekmantown Group constituted of the Theresa Formation, deposited in a marine environment, and the Beauharnois Formation, deposited in lagoonal, intertidal and supratidal environments (Globensky 1987). At its base, the Theresa Formation is made of quartz and dolomitic sandstone, with occasional dolostone increasing in thickness toward the top of the formation and where sandstone thickness oppositely decreases. The Theresa Formation is conformably overlain by the Beauharnois Formation made of dolostone. The Beekmantown Group has an average porosity of 1~2 % (Tran Ngoc et al. 2014). The transition observed in the Beekmantown Group, from quartz-rich sandstone at the base to dolostone at the top is seen to affect the geothermal potential changing from the Theresa Formation to the Beauharnois Formation.

The Chazy, Black River and Trenton groups, unconformably overlying the Beauharnois Formation represent shallow to deep marine environment deposits showing a deepening upward trend (Lavoie 1994). These groups are dominantly constituted of limestone and argillaceous limestone, with occasional dolostone and sandstone. The carbonate content is the main factor affecting the geothermal potential.

Near the top of the Trenton Group, limestone decreases at the expense of the increasing clay until the overlying Utica Shale (Globensky 1987). This transition marks a change toward a deep marine depositional environment resulting in an increase of clay that can reduce the geothermal potential in the Utica Shale. The Sainte-Rosalie Group, subsequently overlying the Utica Shale, comprises siltstone, mudstone, silty mudstone and occasionally dolostone showing a shallowing-upward trend with decreasing clay content toward the top (Globensky 1987).

The Lorraine Group, made of shale, sandstone, siltstone and limestone, overlies the Sainte-Rosalie Group, both of which are turbidites. Molasses of the Queenston Group, on top of the Lorraine Group, are characteristics of a continental to a subaerial deltaic environment (Globensky 1987). Shale with minor sandstone and siltstone including occasional gypsum and anhydrite lenses constitutes the Queenston Group. The heterogeneous rock types of both the Lorraine and Queenstone groups may result in a varying geothermal potential.

Cretaceous intrusions called the Monteregians Hills crosscut the sedimentary sequence of the SLL basin in the southwestern region (Figure 3). They are composed of a large variety of igneous rocks, mostly pyroxenite, gabbro, diorite and pulaskite (Brisebois and Brun 1994). The Monteregians Hills are surrounded by dike systems and have been brought to surface by erosion during the Quaternary glaciations. Igneous rocks of the Monteregian Hills cover a limited area near the surface and have not been considered in this regional assessment of the subsurface thermal conductivity focusing on the sedimentary sequences as a first step.

Host rocks to the south of Quebec are commonly covered by unconsolidated Quaternary deposits originating from the melt of the last ice cap giving birth to the Champlain Sea, which covered older quaternary deposits of preceding glaciations (Globensky 1987). The unconsolidated deposits are made of clay, sand and till and a have a varying thickness ranging from less than 5 m to more than 35 m. The thickness and the nature of the Quaternary deposits can be found in water well records and groundwater databases available for the area, for example the reports of Carrier et al. (2013) and Laroque et al. (2015). The unconsolidated deposits have not been incorporated in this geothermal potential assessment since their thickness varies significantly across the sedimentary basin. This work aimed at identifying regional trends in thermal conductivity that can influence the operation of vertical ground-coupled heat pump systems and was therefore focused on bedrock characteristics. The information presented can be combined with site characteristics, such as overburden thickness and nature, as geothermal heat pump systems are installed to complete system design based on local geological settings. The groundwater level in the SLL basin is relatively shallow and commonly found less than 10 m below the surface (Carrier et al. 2013; Laroque et al. 2015). All host rocks were therefore assumed to be fully saturated.

This description of the SLL basin provides a qualitative understanding of the main factors affecting the conductive heat transfer potential of the rock units, in which ground-coupled heat pump systems can be installed and where further laboratory testing was carried out.

3 Methodology

The work to evaluate the geothermal heat pump potential of the SLL basin consisted in collecting rock samples from outcrops, evaluating their thermal properties in the laboratory and determining the length of borehole that would be needed for a small size ground-coupled heat pump system with a single GHE. The measured thermal conductivities were compared and originally grouped into thermostratigraphic units, defined in this study as consecutive geological layers of similar conductive heat transfer ability. Sedimentary groups or formations were combined or divided to define the thermostratigraphic units that are further constrained by their positions within the sedimentary sequence. This definition is in agreement with thermostratigraphic principles used for exploration of deep geothermal resources for power generation (Gosnold et al. 2012; Sass and Götz 2012) and has been applied in this study to ground-coupled heat pump systems. The borehole length obtained by sizing a typical system, in which the thermal properties of the samples are input parameters, were compared and assigned a low, medium and high geothermal potential to identify the favorability of the thermostratigraphic units. Due to the territory covered and the difficulties to interpolate thermal conductivity values, results were presented on point maps plotted on top of a geological map of the SLL basin to visualize the extent and potential of the thermostratigraphic units.

3.1 Fieldwork

A field campaign was conducted to visit outcrops and collect fifty rock samples representative of each group constituting the sedimentary sequence of the SLL basin (Nasr et al. 2015). Samples were collected from sedimentary beds that appeared most abundant when visiting referenced outcrops that have been studied to define the stratigraphy of the area (Globensky 1987). Forty-five samples were suitable for analysis, which included at least three samples per sedimentary group. A few samples from the proximal Grenville and Appalachian provinces were also collected for comparison purposes. However, more samples would be required to picture the diversity of rock types present in these complex geological provinces to fully assess their geothermal potential. The size of the samples was generally more than 15~20 cm in diameter, to allow measurement of thermal conductivity in the laboratory with a needle probe.

3.2 Laboratory measurements

Collected samples were initially cut and a hole was drilled at the middle of the samples. The size of the needle used for thermal conductivity measurements, and consequently the holes drilled in the samples, was 3.8 mm in diameter and 60 mm in length. The samples were allowed to cool down after drilling for at least a week before conducting thermal conductivity measurements. The probe used was a KD2 pro model from Decagon Devices and encloses one temperature sensor at the center of the needle having a heat injection rate equal to 6 W m^{-1}. Many of the samples broke while drilling the holes, especially friable clays. The analyses were consequently performed on rock samples that were well consolidated and in which it was possible to drill a hole to insert the needle. This has important consequences as dense and well consolidated rocks that can have a higher thermal conductivity tend to be more suitable for measurements than soft and friable rocks that can have a lower thermal conductivity. When showing visible porosity, the samples were immersed in water 48 hours prior to testing for saturation. Thermal conductivity was assumed isotropic for each measurement. Alternatively, dry measurements were performed. A thermal grease compound was applied on the needle to ensure good contact between the needle and the samples.

Thermal conductivity measurements were conducted in the laboratory at room temperature according to the ASTM D5334 methodology (ASTM International 2008). The probe was initially inserted in a reference polyethylene standard of known thermal conductivity equal to 0.37 W m^{-1} K^{-1} and heat was injected once during a period of approximately five minutes followed by five minutes of thermal recovery to make a measurement. The probe was then inserted in a rock sample and heat injection was repeated every hour to make at least five consecutive thermal conductivity measurements and allow sufficient cooling time between each measurement. A reference sample measurement was repeated after the series of rock sample measurements. The two reference sample measurements were averaged to determine a correction factor that is multiplied to the rock sample measurements that are finally averaged to return the final thermal conductivity of the rock sample. This procedure was repeated for each forty-five samples tested.

The thermal conductivity was determined from the heat injection experiments with the slope method originating from a simplification of the infinite line source equation:

$$\lambda = \frac{q}{4\pi m} \qquad \text{eq. 1}$$

where λ (W m^{-1} k^{-1}) is the thermal conductivity, q (W m^{-1}) is the heat injection rate and m is the slope determined from the late temperature increments plotted as function of the logarithmic time. In the analysis of recovery data, the temperature increments are plotted as function of a normalized logarithmic time (t/t_c) to determine the slope, where t_c (s) is the time after heat injection stopped. This time normalization originates from the application of the superposition principle to the infinite line-source equation to reproduce recovery measurements. The two thermal conductivity estimates obtained from the heat injection and recovery data were averaged to provide a single measurement per analysis cycle. The accuracy of the measurements provided by the manufacturer of the needle probe is ± 10 %.

Identification of the volumetric heat capacity for each sample was necessary to find the thermal diffusivity, defined by the ratio of the thermal conductivity over the volumetric heat capacity, and continue to the next step, in which sizing calculations are performed for a typical geothermal system. Thin sections of each rock sample were consequently prepared and analyzed under a petrographic microscope to estimate the main mineralogical phases and the porosity. This data was used to calculate the volumetric heat capacity of the rock samples (Waples and Waples 2004b):

$$\rho_{rock} Cp_{rock} = \rho_{solids} Cp_{solids} (1-n) + \rho_{water} Cp_{water} n \qquad \text{eq 2.}$$

where ρ (kg m^{-3}) is the density, Cp is the specific heat capacity at constant pressure (J kg^{-3} K^{-1}) and n (-) is the porosity fraction. The volumetric heat capacity of the main mineral phases were averaged according to their volume fraction to find the volumetric heat capacity of the solids (Waples and Waples 2004a). This approach used to calculate the volumetric heat capacity yields an approximation whose error has little impact since heat capacity is fairly similar among rock types and the sensitivity of heat storage to the sizing equation is low.

3.3 Geothermal potential evaluation

GHEs are an expensive component of ground-coupled heat pump systems. Host rocks in which fewer GHEs can be installed to offer the same heat transfer potential can be identified as favorable. Sizing calculations were consequently performed to determine the length of GHE that would be needed for a small size building, keeping the same design parameters and changing the subsurface thermal properties according to those found for each sample.

The method given by Philippe et al. (2010) for a system with a single borehole was used to determine the length L (m) of the GHE with:

$$L = \frac{q_{\mathrm{h}} R_{\mathrm{b}} + q_{\mathrm{y}} R_{10\mathrm{y}} + q_{\mathrm{m}} R_{1\mathrm{m}} + q_{\mathrm{h}} R_{6\mathrm{h}}}{T_{\mathrm{m}} - T_{\mathrm{g}}} \qquad \text{eq. 3}$$

where q_h, q_m and q_y (W) are the heat exchange rates with the subsurface, or the ground loads, determined for the maximum hourly load, the monthly average of the design month and the average yearly value, respectively. The effective ground thermal resistances R_{10y}, R_{1m} and R_{6h} (m K W^{-1}) are calculated for a ten year, a ten year plus one month and a ten year plus one month and six hours pulses based on the cylindrical-source equation affected by the subsurface thermal properties (Carslaw 1945; Ingersoll et al. 1954). The term R_b (m K W^{-1}) denotes the borehole thermal resistance associated to the ground heat exchanger and was evaluated with Hellström's line-source method (1991) using a two-dimensional approach. The temperatures at the dominator T_m and T_g (K) are averages for the water in the GHE and the undisturbed subsurface.

The design parameters that were kept constant for each calculation are those of a small residential building with a single GHE that could be a house located in the SLL (Table 1). The system is sized according to heating loads, which are negative for heat to be extracted from the subsurface. The peak heating load imposed to the ground is 7.5 kW, representing a peek heating capacity of 10.5 kW (3 tons) for the building when considering a coefficient of performance equal to 3.5 for the heat pump. The GHE fluid is for water mixed with 25 % propylene glycol providing a -10 ºC freeze protection and a minimum heat pump inlet temperature of -2 ºC have been selected. The borehole characteristics are those of typical GHE installed in the SLL made with a single U-pipe having space clips and inserted in 0.152 m diameter borehole that is filled with thermally enhanced grout made of quartz sand and bentonite. The subsurface temperature was assumed to be 8 ºC and inferred from maps of Majorowicz et al. (2009). This temperature is a rough average for the study area that is assumed constant at each location since the calculations are performed to identify the effect of the subsurface thermal properties on the required borehole length.

The sizing calculations were repeated according to the thermal conductivity and heat capacity determined for each sample in the laboratory. The borehole lengths obtained were classified in three categories, short, medium and long, assigned to a high, medium and low geothermal potential, respectively. The geothermal potential was associated to each sample rather than to thermostratigraphic units since there can be different potential within heterogeneous rocks grouped in a unit. This approach is suitable to identify prominent trends within units and compare rock types of a given area among each other, bearing in mind that the potential is relative to the range of thermal conductivity obtained for the study area.

Table 1. Constant design parameters considered for sizing calculations

Parameter	Unit	Value
Peak hourly ground load	W	-7500
Monthly ground load	W	-3750
Yearly average ground load	W	-998
Undisturbed subsurface temperature	ºC	8
Fluid heat capacity	J kg^{-1} K^{-1}	3930
Total mass flow rate per W of peak hourly ground load	kg s^{-1} W^{-1}	78
Minimum heat pump inlet temperature	ºC	-2
Borehole radius	M	0.076
Pipe inner radius	M	0.0172
Pipe outer radius	M	0.0210
Grout thermal conductivity	W m^{-1} K^{-1}	1.73
Pipe thermal conductivity	W m^{-1} K^{-1}	0.40
Center to center distance between pipes	M	0.10
Internal convection coefficient	W m^{-2} K^{-1}	3200

3.4 Map preparation

Although forty-five samples were collected and analyzed in the laboratory to classify the thermostratigraphic units of the SLL basin, those were insufficient to interpolate thermal conductivity assessments between samples. The area covered by the SLL basin in Quebec is roughly 20 000 km^2 and a very important number of samples would have to be collected to interpolate thermal conductivity measurements with geostatistical methods. The sample locations were consequently plotted, with a dot size proportional to the thermal conductivity measured in the laboratory, on a geological map showing the formations of the sedimentary sequence in background to illustrate the ability of the host rock to transfer heat by conduction. A second dot map was prepared showing the thermostratigraphic units and the geothermal potential determined from the borehole lengths with each sample using superimposed color hexagons and circles to illustrate the favorability to ground-coupled heat pump systems. The resulting maps provide a first data set to help geothermal system designers to find information about the host rock thermal conductivity and conductive heat transfer potential for closed-loop geothermal systems in the SLL basin.

4 Results

The range in thermal conductivity measured on the forty-five samples varies from 2.0 to 6.9 W m^{-1} K^{-1}, with a mean and standard deviation respectively equal to 3.57 and 1.46 W m^{-1} K^{-1} (Table 2). The obtained thermal conductivity values are described for each thermostratigraphic unit with respect to the distribution of laboratory measurements specific to the SLL basin and the range of values commonly expected for sedimentary rocks (Clauser 2014b).

The Grenvillian basement below the sedimentary sequence has low to high thermal conductivity ranging from 2.3 to 4.2 W m^{-1} K^{-1}, which can be explained by varying quartz and plagioclase content. Despite the limited number of samples, rocks of the Grenville were classified in a thermostratigraphic unit since its variability contrast to that of the SLL sedimentary rocks.

The Potsdam sandstone at the base of the sedimentary sequence shows the highest thermal conductivity, typically above 6.0 W m^{-1} K^{-1}. The high quartz content of the Cairnside Formation is responsible for the peak thermal conductivity values of the sedimentary sequence. Thin sections analyses of samples collected in this study revealed a quartz content above 85 % for the Cairnside and Covey Hill formations, explaining the high thermal conductivity. Both formations, the Cairnside and the Covey Hill, have therefore been classified in a single thermostratigraphic unit.

The overlying Theresa Formation dominantly made of sandstones similarly has a high thermal conductivity, with two samples having values of 4.0 and 5.9 W m^{-1} K^{-1}. The transition toward dolostone in the Beauharnois Formation has a strong effect on thermal conductivity decreasing toward moderate values ranging from 2.7 to 4.2 W m^{-1} K^{-1}. The Theresa and the Beauharnois formations, although in the same geological group, have been classified in two distinct thermostratigraphic units because of the increase in dolomite concentration toward the top. The thermal conductivity of the Theresa Formation is generally intermediate between the Potsdam Group and the Beauharnois Formation, showing a transition that justifies the classification in distinct thermostratigraphic units.

Table 2. Thermal properties and geothermal potential of thermostratigraphic units

Thermostratigrahic unit	Sample number	Lithology	Thermal conductivity (W m^{-1} K^{-1})	Thermal diffusivity (m^2 j^{-1})	Borehole length (m)	Geothermal potential
Appalachians	14MN38	Siltstone	3.41	0.14	141	M
	14MN40	Siltstone	3.74	0.23	139	M
	14MN41	Limestone	2.60	0.10	163	L
Queenston and Lorraine	14MN24	Siltstone	2.96	0.11	151	M
	09EK330	Siltstone	3.40	0.13	140	M
	14MN21	Mudstone	2.70	0.10	159	M
	14MN23	Mudstone	2.93	0.11	152	M
	09EK326	Mudstone	2.00	0.08	189	L
	09EK333	Siltstone	3.33	0.13	142	M
	09EK344	Siltstone	3.00	0.12	150	M
Sainte-Rosalie and Utica	14MN35	Mudstone	2.26	0.08	176	L
	14MN36	Siltstone	4.10	0.17	128	H
	09EK335	Arg. dolostone	2.29	0.08	173	L
	14MN27	Siltstone	2.52	0.09	165	L
	14MN29	Siltstone	2.30	0.09	174	L
	14MN30	Mudstone	2.00	0.07	189	L
Trenton, Black River and Chazy	14MN10	Limestone	2.71	0.10	159	M
	14MN13*	Arg. limestone	2.98	0.11	150	M
	14MN14	Limestone	2.63	0.10	161	L
	14MN17	Limestone	2.50	0.09	166	L
	14MN19*	Limestone	3.20	0.12	144	M
	14MN28	Arg. limestone	2.63	0.10	162	L
	14MN31	Arg. limestone	2.60	0.10	163	L
	14MN32	Arg. limestone	2.67	0.10	161	L
	09EK311	Arg. limestone	2.60	0.10	162	L
	09EK320	Limestone	2.60	0.10	162	L
	09EK324	Limestone	4.15	0.17	127	H
Beekmantown (Beauharnois)	14MN09	Limestone	2.70	0.10	159	M
	14MN11	Dolostone	2.85	0.11	154	M
	14MN12	Dolostone	4.24	0.15	124	H
	14MN20	Dolostone	3.48	0.12	137	M
	09EK304	Dolostone	3.60	0.13	135	M
Beekmantown (Theresa)	14MN01*	Sandstone	5.88	0.22	107	H
	14MN16	Sandstone	4.00	0.16	129	H
Potsdam	14MN02*	Sandstone	6.90	0.29	101	H
	14MN03*	Sandtsone	6.67	0.27	102	H
	14MN04*	Sandtsone	6.43	0.24	103	H
	14MN05*	Sandtsone	6.43	0.23	110	H
	14MN06*	Sandtsone	6.31	0.27	105	H
	14MN07*	Sandtsone	6.55	0.28	103	H
	14MN08*	Sandtsone	6.05	0.24	106	H
Grenville	14MN18	Igneous	2.25	0.09	178	L
	14MN33	Igneous	2.71	0.11	160	L
	14MN34	Igneous	2.51	0.12	170	L
	09EK341	Igneous	4.18	0.17	127	H

Abbreviations for the geothermal potential: L; low ≥ 160 m, M; moderate > 130 m < 160 m, H; high ≤ 130 m. Arg.: argillaceous. * Sample with visible porosity that has been saturated for thermal conductivity measurement.

The change in mineralogy originating from the depositional environment resulting in dominant limestone content with some clay for the Trenton, Black River and Chazy groups have a strong effect on thermal conductivity ranging from 2.5 to 4.2 W m^{-1} K^{-1}. Observations indicate that thermal conductivity of limestone and argillaceous limestone is most commonly between 2.5 to 3.0 W m^{-1} K^{-1}, and can occasionally be higher in sedimentary beds containing dolomite and quartz. Dolostone and sandstone layers, mostly found at the base in the Chazy Group, are thinner than those of the limestone and argillaceous limestone layers and the three groups, Trenton, Black River and Chazy, have therefore been classified in a single thermostratigraphic unit.

The increase in clay content in the Utica Shale and the Sainte-Rosalie Group affects the thermal conductivity that is generally below 2.5 W m^{-1} K^{-1} in those two geological units. A low value of 2.0 W m^{-1} K^{-1} has been observed in the Utica Shale. One sample with a high thermal conductivity of 4.1 W m^{-1} K^{-1} was found in the Sainte-Rosalie Group and was associated with a greater quartz content that is uncommon. The Utica Shale and the Sainte-Rosalie Group were classified in a single thermostratigraphic unit because of their similar low thermal conductivity.

Lithologies are variable in the overlying Lorraine and Queenston groups of shallow marine to continental depositional environment, which affects thermal conductivity values that are generally moderate and range from 2.0 to 3.4 W m^{-1} K^{-1}. Shale is the dominant lithology and is mixed with other rock types, explaining the variations in thermal conductivity for those two groups that have been classified in a single thermostratigraphic unit. Samples collected for the proximal Appalachians have a thermal conductivity that is similar to that of the adjacent Lorraine Group. Major faults separate the Appalachians from the Loraine Group and the Appalachians have been classified in a distinct thermostratigraphic unit.

The borehole length calculated for a typical geothermal system of small size with the thermal properties measured in the laboratory reveals the geothermal potential of each sample and the dominant trend for the thermostratigraphic units (Table 2). A high, moderate and low geothermal potential for closed-loop systems has been assigned to borehole lengths less than or equal to 130 m, between 130 to 160 m and greater or equal to 160 m, respectively. The samples with a low, medium and high geothermal potential show a thermal conductivity less than 2.7 W m^{-1} K^{-1}, between 2.7 and 3.7 W m^{-1} K^{-1}, and above 4.0 W m^{-1} K^{-1}, respectively. The thermostratigraphic units with samples having a dominantly high thermal conductivity, such as the Potsdam Group and the Theresa Formation, have a most frequently high geothermal potential. The thermostratigraphic units with samples of mainly low thermal conductivity, like the Utica Shale and the Sainte-Rosalie Group, have a most frequently low geothermal potential, although punctual deviation characteristic of heterogeneity was observed.

The thermal conductivity measurements and the associated thermostratigrahic units plotted on the geological map (Figures 3a and b) suggest a high geothermal potential in the Southwest of the SLL basin, were rocks of the Potsdam Group and the Theresa Formation are found near the surface. Toward the Northeast of the SLL basin, the basal sandstones are buried below the Trenton, Black River, Chazy, Utica and Sainte-Rosalie groups with a lower geothermal potential. A moderate geothermal potential associated to the Lorraine and Queenston groups is more common at the center of the synclinal defining the dominant geological structure in the SLL basin.

It is important to recall that thermal conductivity measurements made with a needle probe can be difficult to realize for friable rocks composed of shale of low thermal conductivity. Consequently, laboratory measurements may be slightly higher than in situ measurements. Additionally, the comparison made between the themostratigraphic units is relative to the range of values obtained for the study area. Thermal conductivity measurements below 2.5 W m^{-1} K^{-1} were classified in this work as low, especially when compared to quartz rich sandstone of thermal conductivity greater than 6.0 W m^{-1} K^{-1}, but could be considered as moderate when taking into account the range of thermal conductivity observed for geological materials that can be as low as 0.6 W m^{-1} K^{-1}.

5 Discussion

Thermostratigraphy, which can be considered as a stratigraphic concept such as lithostratigraphy or biostratigraphy, focuses on the links between rock sequences, including their origin and composition, and thermal property variations, mainly thermal conductivity. It can be used to tie subsurface temperature profiles to thermal conductivity and heat flux with the application of Fourier's law for heat conduction. The use of thermostratigraphic principles is common in the study of terrestrial heat flow and the assessment of deep geothermal resources for power generation. For example, Gosnold et al. (2012) extrapolated temperature at depth in the Williston basin of North Dakota with thermostratigraphic principles making use of heat flow assessments and thermal conductivity measurements. Other recent examples of thermostratigraphic assessment in the context of deep geothermal resources evaluation in sedimentary basins of the United States have been described by Gosnold et al. (2010), Crowell and Gosnold (2011) and Crowell et al. (2011).

Rock thermosequences were further involved in the definition of thermofacies presented by Sass and Götz (2012) for the exploration of geothermal reservoirs to produce electricity. The concept is to compare thermal conductivity and permeability of rock samples to classify rock units of a geothermal system from petrothermal, or conductive heat transfer dominated, to hydrothermal, or convective heat transfer dominated. This principle has been applied in various geological environments, for example the Molasse sedimentary Basin in Germany (Homuth et al. 2015), the Tauhara hydrothermal field in New Zealand (Mielke et al. 2015) and volcaniclastics of the Valley of Mexico (Lenhardt and Götz 2015). Aretz et al. (2016) presented a recent study where depositional environments and diagenesis processes are linked to thermal and hydraulic properties in geothermal reservoirs of sedimentary origin.

A similar attempt to classify rock thermosequences, but in the scope of shallow geothermal resources for ground-coupled heat pump systems, is presented in this study. The thermostratigraphic units, defined as consecutive geological layers of similar conductive heat transfer potential, links the geological environment to mineralogy changes and the resulting subsurface thermal conductivity. It can be used to define favorability to geothermal heat pumps at a regional scale, where interpolation between thermal conductivity measurements is difficult for large territories. The results presented on point maps are an alternative to assigning thermal conductivity ranges to geological units, for example done by Di Sipio et al. (2014), when thermal conductivity variations are important, likely more than 0.5 W m^{-1} K^{-1} within a unit. The thermostratigraphic assessment presented in this study can help to design ground-coupled heat pumps that dominantly operate under conductive heat transfer with the subsurface. Thermal conductivity values can be used as a basis for geothermal potential assessment according to geothermal heat pump simulations (Galgaro et al., 2015), in which valuable results are supported by field data. Simple sizing calculations with inputs from laboratory measurements of thermal conductivity were used in this study to evaluate the length of GHE needed for a given heat pump system to define the geothermal potential. The assessment provided classes and thermal conductivity ranges for thermostratigraphic units to be used in the absence of a thermal response test to design systems. The concept is not to replace in situ measurements of the subsurface thermal conductivity but to use this assessment to guide design of small systems, where a field test can be uneconomic (Robert and Gosselin 2014), or for screening calculations of larger systems, where a test can be performed afterward to validate field conditions. A designer could use the map provided in this study to locate its geothermal system and infer the possible thermal conductivity for the bedrock encountered. The thickness of the overburden and its thermal conductivity, which can be estimated from databases of the geological records, shall be considered for a complete assessment of the subsurface over the depth of the planned borehole. Nevertheless, the maps presented provide information about the thermal conductivity of the bedrock, an essential parameter to design and simulate geothermal systems that was until now difficult to evaluate in the SLL basin.

6 Conclusions

The geothermal heat pump potential of the St. Lawrence Lowlands (SLL) basin was evaluated based on a first thermostratigraphic assessment of rock sequences located in Quebec, Canada. Sizing calculations performed to determine the length of a ground heat exchanger for a small residential building, according to thermal properties measured in the laboratory on rock samples collected in outcrops, provided the basis to determine the favorability of geothermal heating and cooling systems. The analysis revealed a high geothermal potential for basal sandstones of the Potsdam Group that formed in a rift environment. The high quartz content is responsible for the high thermal conductivity of those sandstones. The overlying rock units of the Theresa and Beauharnois formations, the Chazy, Black River and Trenton groups as well as the Utica Shale and the Sainte-Rosalie Group deposited in a passive margin evolving to a foreland basin. The resulting transition of dolostone to argillaceous limestone and then shale exhibited a high to low geothermal potential decreasing toward the top. The change in mineralogy related to the depositional environment is the dominant factor affecting the subsurface thermal conductivity. Turbidites and molasses of the overlying Lorraine and Queenston groups tend to be more heterogeneous and generally had a moderate geothermal potential, although the potential can change laterally and stratigraphically in the sedimentary basin.

The present study provides an original contribution to help design geothermal heat pump systems that will be installed in the SLL, where most population is found in the province of Québec. The results showed how to link subsurface thermal properties to mineralogy, rock type and depositional environments to improve geothermal heating and cooling, a human activity that can benefit to the environment with significant energy savings. This geoscientific mapping exercise offers new data downloadable as supplementary material accompanying the paper to help develop green buildings using sustainable energy sources. The regional geothermal potential evaluation was conducted over an area of about 20 000 km^2 and will be detailed in smaller areas, where the energy needs and the building density are most important. Units of the Grenville and the Appalachians geological provinces, representing regions with significant population when adjacent to the SLL, were studied for comparison with rocks of the SLL basin but will require more samples to picture the diversity of rock types in these complex geological environments. A study focusing on the Grenville and the Appalachians would obviously result in the identification of several thermal conductivity classes. The Beekmantown Group within the SLL basin needs to be studied in more detail to better characterize the transition from high to medium geothermal potential in the Theresa to Beauharnois formations changing from sandstone to dolostone. Lateral facies changes in the basin can be included in further studies to refine the geothermal potential assessment. Next studies will focus on data collection with a higher spatial resolution in smaller areas of greater interest to interpolate thermal properties with geostatistical methods.

7 Acknowledgements

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Figure and captions

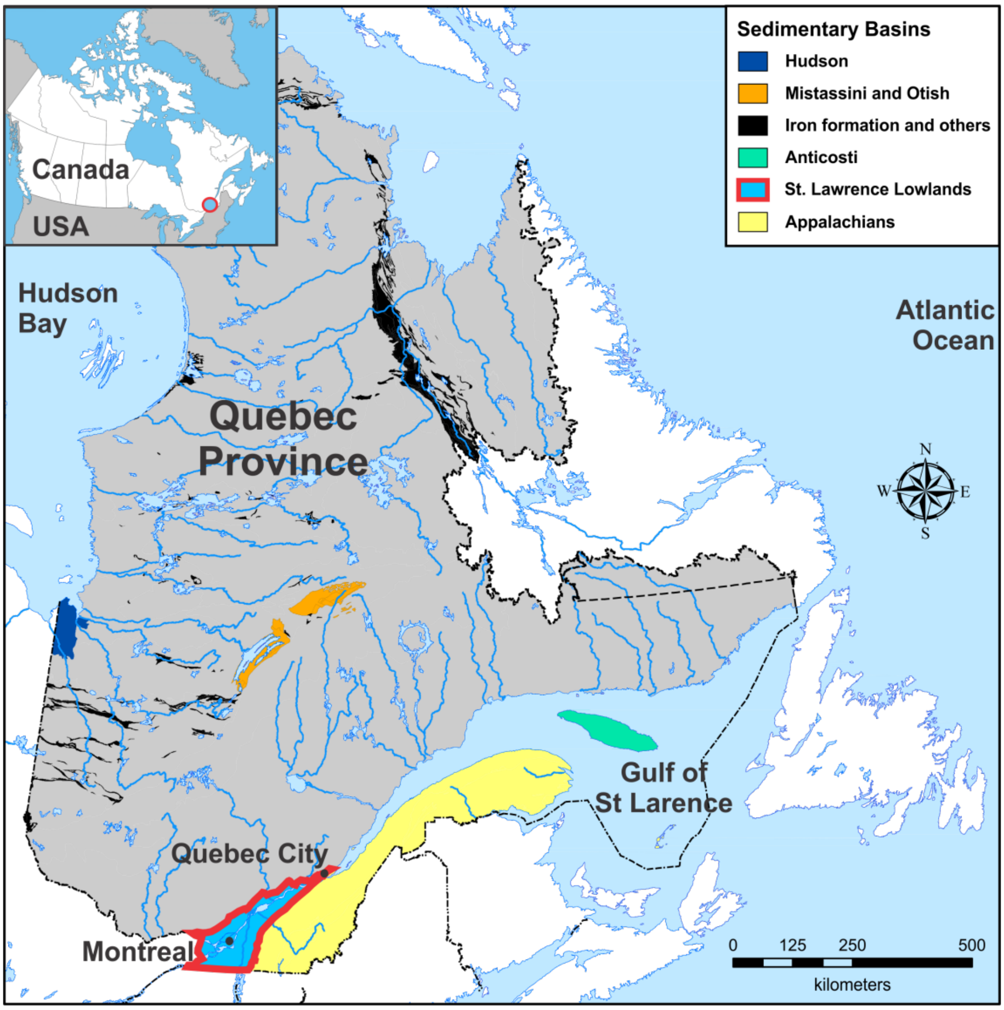


Figure 1. Location of the study area in St. Lawrence Lowlands and other sedimentary basins in the province of Quebec, Canada.

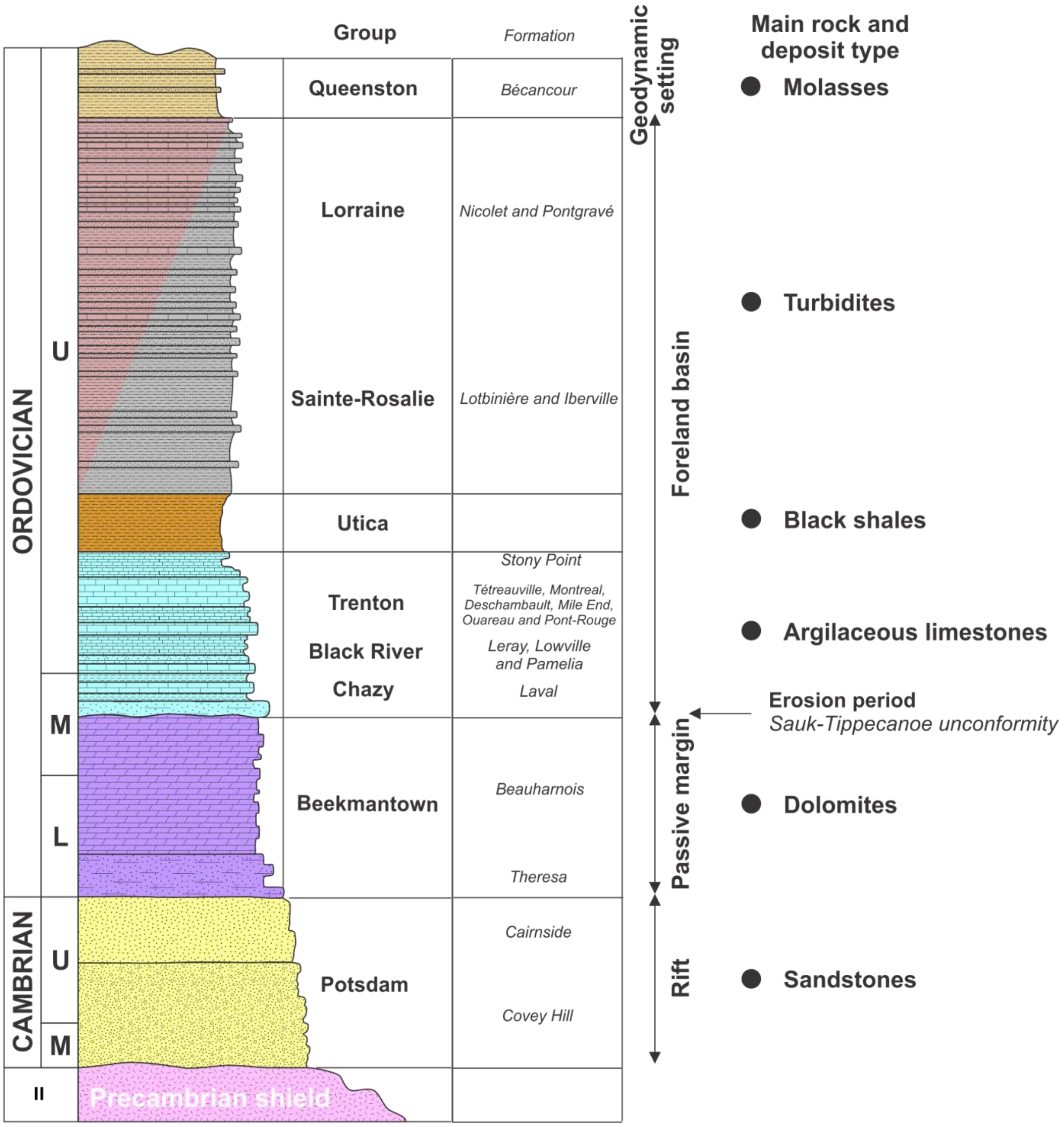
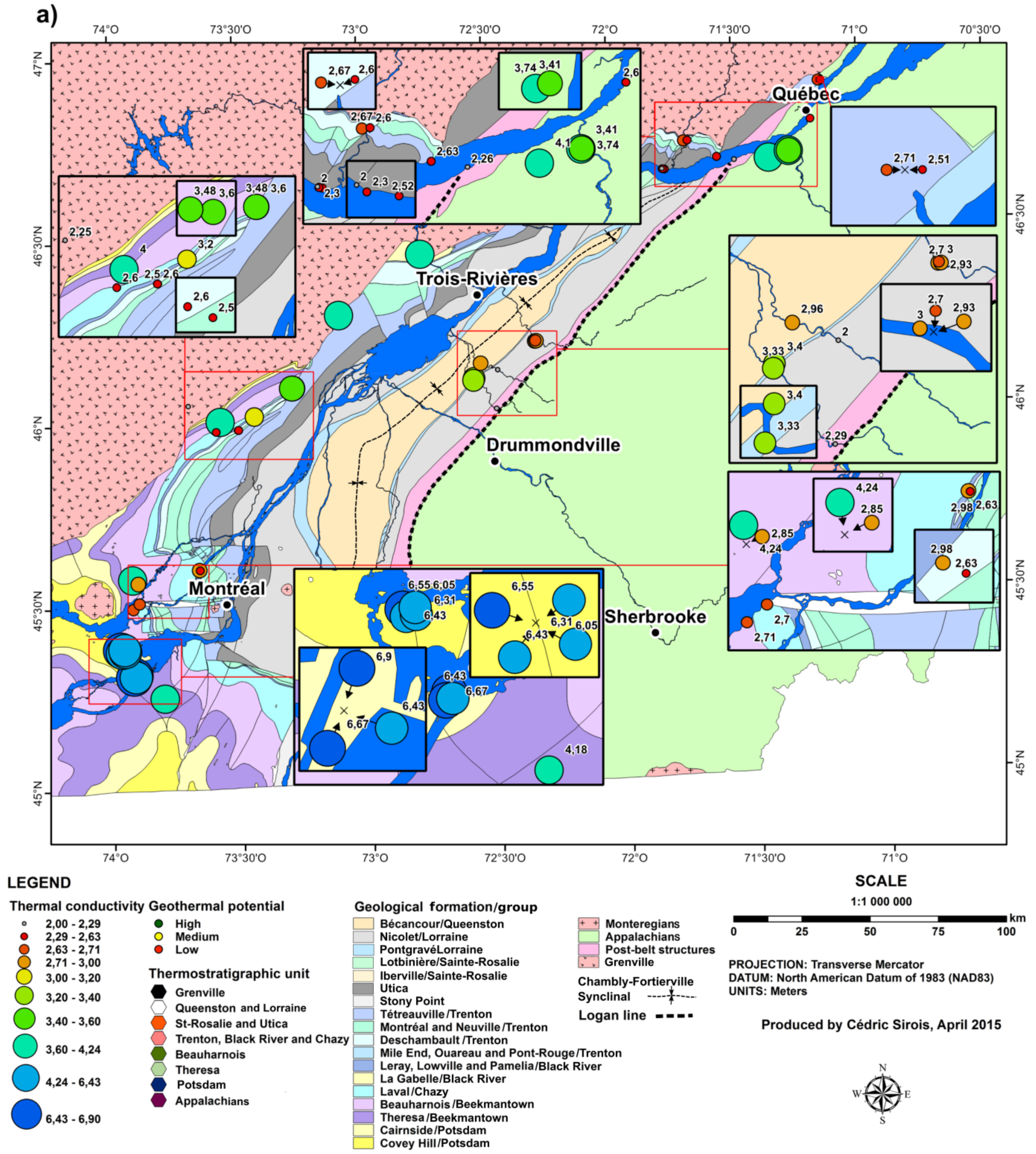


Figure 2. Stratigraphic column showing the St. Lawrence Lowlands sedimentary sequence (Comeau et al. 2012).


a)
Québec
Trois-Rivières
Drummondville
Montréal
Sherbrooke
LEGEND
Thermal conductivity
2,00 - 2,29
2,29 - 2,63
2,63 - 2,71
2,71 - 3,00
3,00 - 3,20
3,20 - 3,40
3,40 - 3,60
3,60 - 4,24
4,24 - 6,43
6,43 - 6,90
Geothermal potential
High
Medium
Low
Thermostratigraphic unit
Grenville
Queenston and Lorraine
St-Rosalie and Utica
Trenton, Black River and Chazy
Beauharnois
Theresa
Potsdam
Appalachians
Geological formation/group
Bécancour/Queenston
Nicolet/Lorraine
PontgravéLorraine
Lotbinière/Sainte-Rosalie
Iberville/Sainte-Rosalie
Utica
Stony Point
Tétreauville/Trenton
Montréal and Neuville/Trenton
Deschambault/Trenton
Mile End, Ouareau and Pont-Rouge/Trenton
Leray, Lowville and Pamelia/Black River
La Gabelle/Black River
Laval/Chazy
Beauharnois/Beekmantown
Theresa/Beekmantown
Cairnside/Potsdam
Covey Hill/Potsdam
Monteregians
Appalachians
Post-belt structures
Grenville
Chambly-Fortierville Synclinal
Logan line
SCALE
1:1 000 000
0 25 50 75 100 km
PROJECTION: Transverse Mercator
DATUM: North American Datum of 1983 (NAD83)
UNITS: Meters
Produced by Cédric Sirois, April 2015

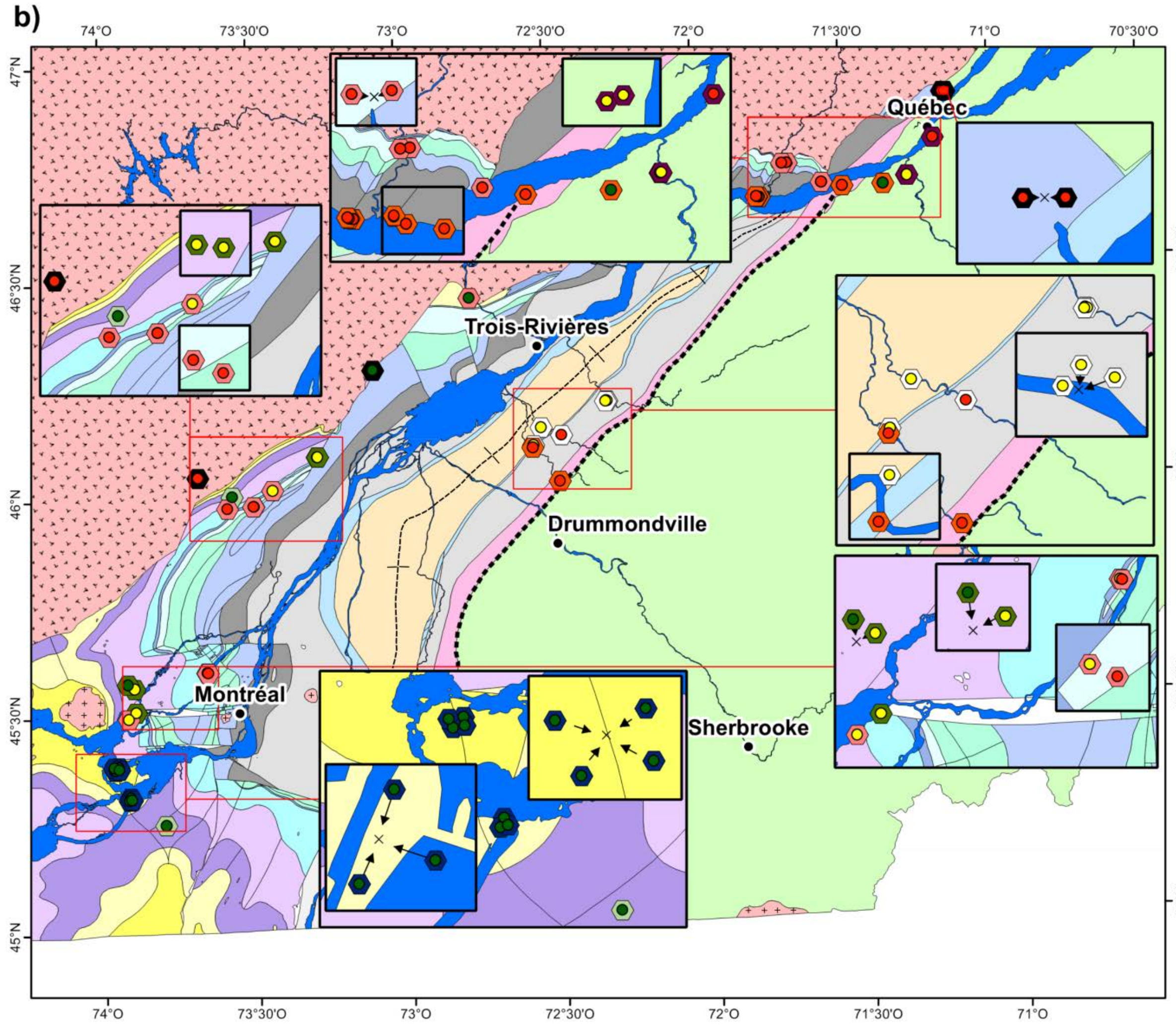


Figure 3. Geological map of the St. Lawrence Lowlands showing a) thermal conductivity measurements and b) geothermal potential assessment of thermostratigraphic units.