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Geothermal Potential of Northern Québec: A Regional Assessment

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ABSTRACT

28 sites with geothermal data were compiled into three distinct geological provinces (Superior, Churchill and Grenville) of the Canadian Shield (Northern Québec) to better characterize their geothermal potential. Temperature profiles were created for each site to evaluate the geothermal resource at a depth of up to 5 km. Low average heat flow is observed of respectively 30.8, 32.1 and 34.4 mW/m^2 for the Grenville, Superior and Churchill geological provinces.

After reviewing theoretical rock thermal conductivities, a distribution map of mean thermal conductivity of the Province of Québec was created to anticipate best and worst case scenarios for each geological province. Regions with a high thermal conductivity of the ground can be favorable to geothermal heat pump systems while a low thermal conductivity can be appropriate for thermal energy storage systems and deep direct use wells tapping warm aquifers with greater geothermal gradient.

1. Introduction

Access to clean and affordable energy is critical to the development of communities and natural resources of Northern Québec and elsewhere in the Canadian North. Indeed, hydrocarbons transported by truck, train and boat are today the main source of heat and electricity in the North, a situation that comes at a high financial and environmental cost. A variety of options of local renewable energy supplies have been examined to date, ranging from small-scale solar systems to wind generation and underwater turbines. However, usage of shallow and deep geothermal energy resources has not been fully considered yet.

Geothermal technologies offer an alternative that can be used to diversify energy sources and reduce greenhouse gas emissions of communities and mine sites. Recent studies have shown significant geothermal energy potential spread over broad regions of Canada (Grasby et al., 2012; Majorowicz and Grasby, 2013). This energy resource can be used to produce heat from a low temperature medium using heat pumps or directly exploiting warm aquifers with modern high efficiency heat exchangers (> 90 % efficiency) as well as producing electricity with resources above 100 ºC. The key advantage of geothermal technologies in remote regions, compared to other renewable options such as solar and wind, is the high capacity factor and the baseload energy supplied essential for space heating of northern buildings. This could give rise to new business activities of great benefit to northern communities, such as greenhouse for producing fruits and vegetables locally.

However, the extent of geothermal resources available in the North is still largely unknown. The region is vast and the subsurface thermal properties characterizing shallow and deep geothermal resources vary greatly. A better knowledge of these resources can help to extend geothermal technologies to Northern Québec and initially test new simulation approaches to determine if geothermal energy is a viable alternative in the North.

2. Background information

The Northern Québec territory (Eastern Canada) of nearly 1.2 million km^2 representing about 72 % of the total land surface area of the province is located north of the 49th parallel (Figure 1). It has a scattered population of over 120,000 people, whom one-third are Aboriginals from four nations (Inuit, Cree, Innu and Naskapi) living in 31 communities, along the coasts or river estuaries, accessible either by plane, or, during the summer and fall, by boat (Figure 1).

Furthermore, the area is richly endowed with natural resources and contains extensive mineral deposits accounting for Québec’s entire production of different minerals. It currently accounts for all the nickel, cobalt, platinum group elements, zinc, iron ore and ilmenite produced in Québec. It is also the source of a large part of Québec’s precious metal production, mainly in the form of gold. The area covered additionally has enormous undeveloped potential for apatite, lithium, vanadium, diamond, graphite and rare earth elements. Currently, there are 11 active mines and 16 mining projects in advanced phase (Figure 1).

Surface annual mean temperatures ranging from -9 to 2 ºC near the ground surface (Figure 2) and the presence of permafrost up to a thickness of 500 m (Figure 3) are two major characteristics of the shallow subsurface in Northern Québec. Temperature of the shallow subsurface has been inferred from the meteorological record using the empirical equation for the undisturbed ground temperature proposed by Ouzzane et al. (2015). The undisturbed ground temperature refers to the temperature deep enough (typically at about 8 m deep) in the ground that remains almost constant throughout the year. For example, the undisturbed ground temperature obtained for the village of Kuujjuaq is -1 °C, while the surface annual mean temperature is -6 °C. However, there are strong seasonal variations that changes the surface temperature to -25 °C in winter and above 10°C in summer (Figure 4).

The Northern Québec territory is part of the Canadian Shield physiographic region dominated by a relief of low hills, undulating plains and plateaus punctuated by three mountain ranges. The core of the Canadian Shield is part of the Superior geological province of late Archean age (2.85-2.65 Ga) composed mainly of crystalline rocks (Simard, 2000; Figure 1). The northeastern part is located in the Churchill geological province (2.8 Ga-1.8 Ma), composed mainly of volcano-sedimentary rocks affected by various degrees of metamorphism. The Grenville geological province (2.65-0.97) constitutes the southeastern part and is characterized by a high degree of metamorphism.

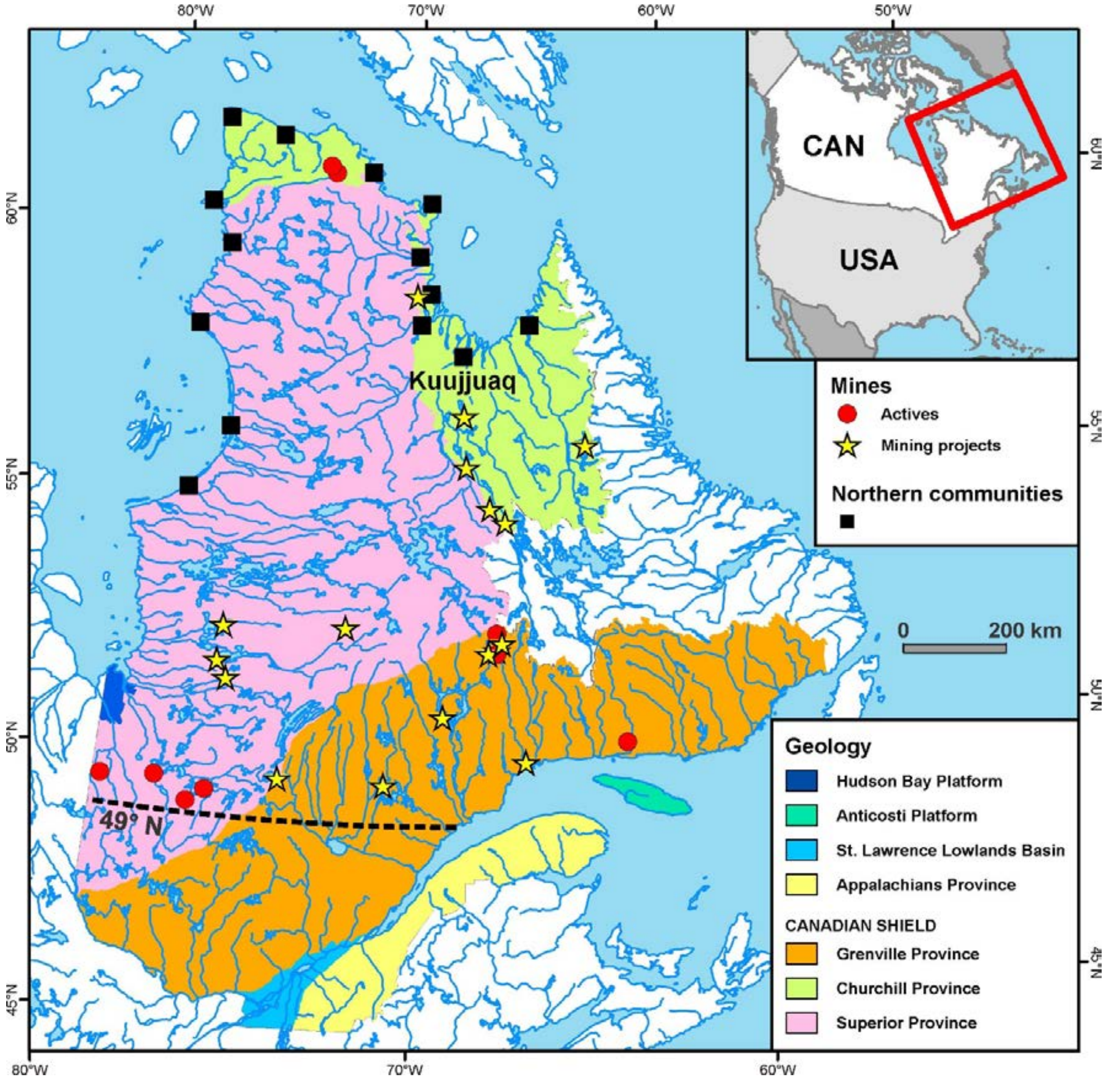

Figure 1: General geological map of the Province of Québec.

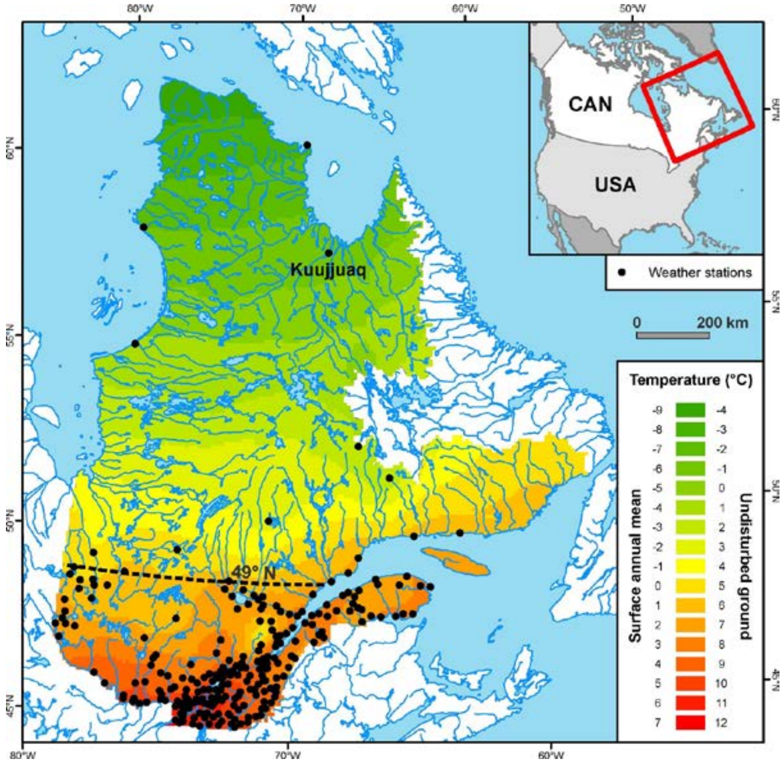

Figure 2: Surface annual mean and undisturbed ground temperatures distribution of the Province of Québec (MDDELCC, 2016).

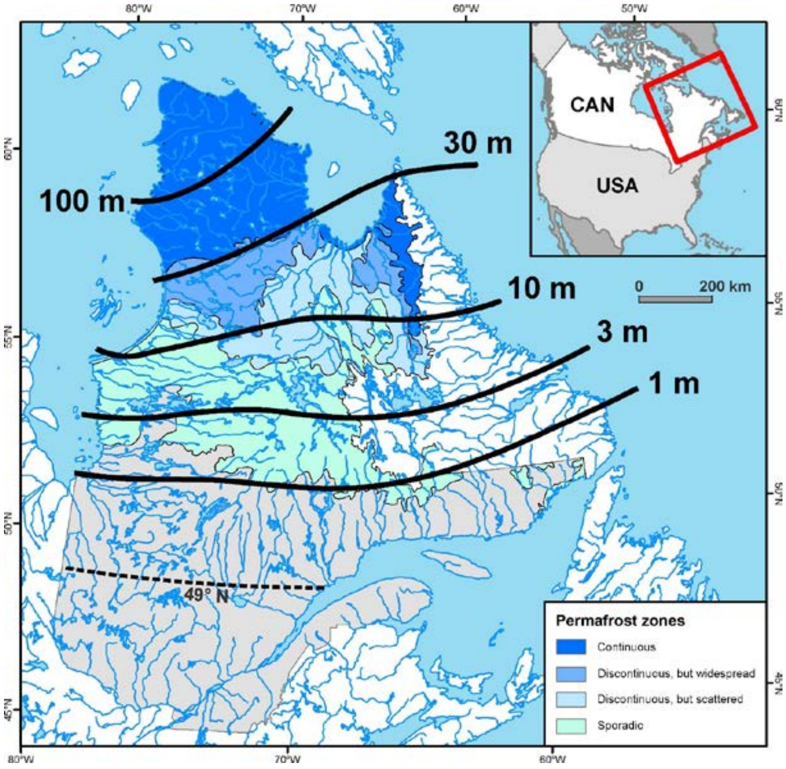

Figure 3: Permafrost distribution and depth in the Province of Québec (Lemieux et al., 2016).

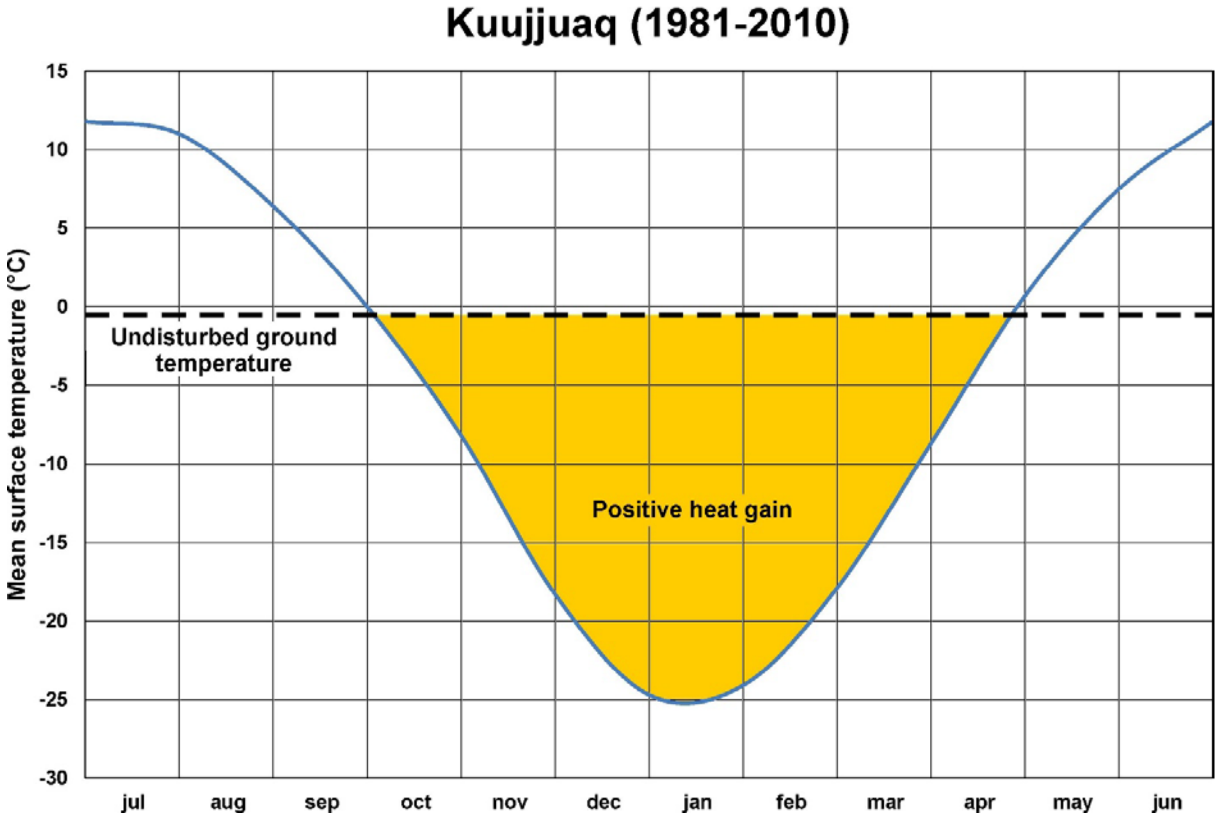

Figure 4: Monthly average atmospheric temperature in Kuujjuaq from 1981 to 2010 (Environment and Climate Change Canada, 2007). Location of Kuujjuaq is shown on Figure 2.

3. Methodology

3.1 Geothermal data

Scarce geothermal data, such as heat flow values, are found throughout Northern Québec (Figure 5). Table 1 presents twenty-eight sites with thermal conductivity, heat generation and heat flow data available for this northern area, divided into three distinct geological provinces: Grenville, Superior and Churchill, where heat flow values ranges from 20 to 47 mW/m^2. This low average heat flow is typical of the Canadian Shield (Majorowicz and Minea, 2015), where data of Table 1 show a mean of respectively 30.8, 32.1 and 34.4 mW/m^2 for the Grenville, Superior and Churchill geological provinces (Figure 5).

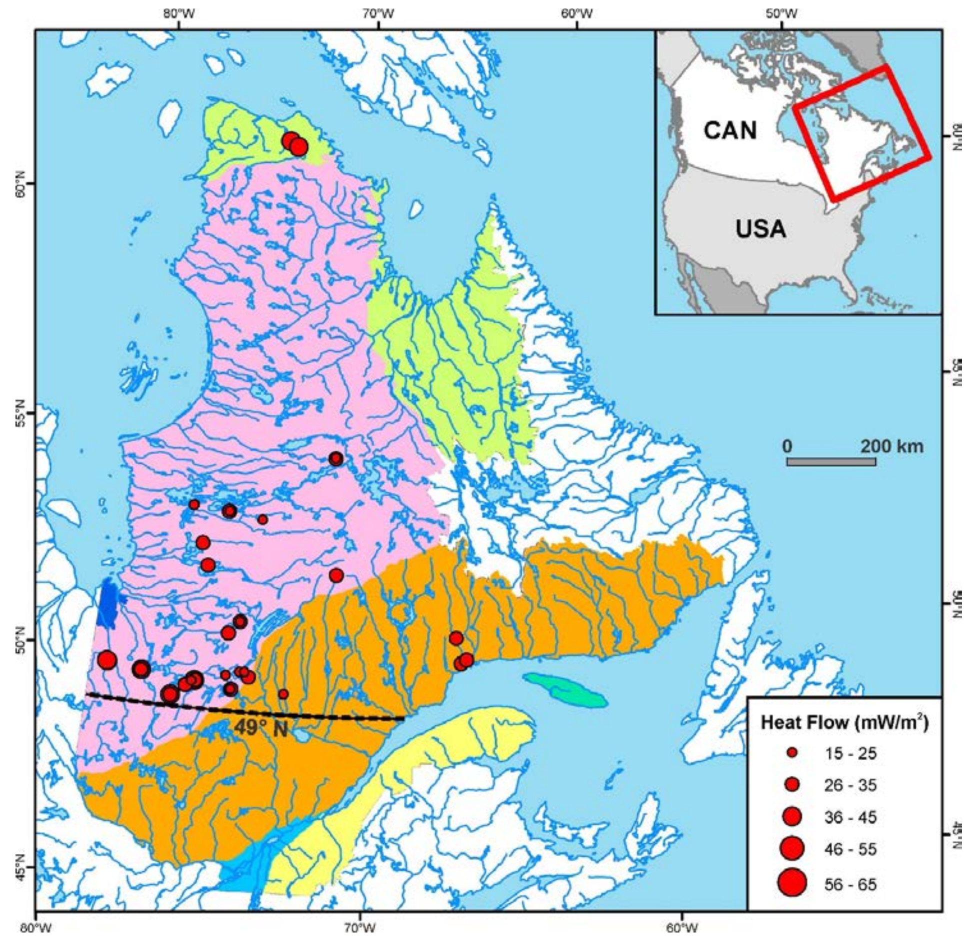

Figure 5: Distribution of heat flow data available in the Canadian Shield. See Figure 1 for the geology legend.

3.2 Extrapolated temperatures at depth

Temperature values were calculated and extrapolated at geothermal resource depth, taking into account the surface heat flow, the thermal conductivity and heat generation rate at the location of geothermal data. Temperature values at depth were obtained using the linear decrease relationship theory that characterizes heat generation effect (Jessop, 1990):

$$T_z = T_0 + \left(\frac{Q_0 \cdot z}{\lambda}\right) - \left(\frac{A \cdot z^2}{2\lambda}\right)$$

where Tz (°C) is the temperature at depth z, T_0 (°C) is the undisturbed ground temperature, Q_0 (W/m^2) is the surface heat flow, z (m) is the depth below surface, λ (W/m·K) is the effective thermal conductivity and A (W/m^3) is the average heat generation rate.

Table 1: Thermal parameters of well sites for calculation of temperature profiles.

Site #	Name	North (°)	East (°)	Thermal cond. (W/mK)	Heat gen. (μW/m^3)	Heat flow (mW/m^2)	Geothermal gradient (mK/m)	Source
Grenville Province								
4	Clarke City	50.21	-66.64	2.1	0.1	30.0	15.4	6
8	Crevier	49.47	-72.77	1.9	1.0	28.0	13.0	3
24	Rivière Sainte-Marguerite	50.78	-66.78	1.7	0.1	33.0	18.2	4
26	Sept-Îles	50.30	-66.45	2.0	0.0	32.0	15.5	6
			Average	**1.9**	**0.3**	**30.8**	**15.5**	
Superior Province								
1	Boyvinet	49.60	-75.98	3.2	0.4	31.0	8.0	5
2	Camp Coulon	54.79	-71.29	3.3	1.4	27.9	7.0	9
3	Chapais	49.79	-74.81	4.0	0.2	26.5	5.4	3, 4
5	Clearwater	52.21	-75.81	2.6	0.5	33.1	11.9	9
6	Conlagas	49.49	-76.17	3.2	0.4	31.0	8.5	5
7	Corvet	53.32	-73.92	2.8	0.6	26.8	8.6	9
9	Desmaraisville	49.61	-75.88	3.4	0.6	34.1	9.6	3, 4
10	Eastmain River	52.17	-76.46	2.9	0.6	33.5	9.4	10
11	Éléonore	52.70	-76.08	2.5	1.0	31.3	11.8	9
12	Frotet-Troïlus	51.01	-74.47	2.6	0.8	29.0	9.6	7
13	Gamache	49.48	-74.61	2.9	0.1	28.0	8.8	5
14	Grevet	49.24	-76.65	4.3	0.5	41.0	8.3	5
15	Île Marguerite	49.89	-74.17	3.5	0.1	27.0	6.4	5
16	Lac au Doré	49.88	-74.33	3.3	0.1	28.0	7.3	5
17	Lac Girafe	52.18	-71.10	6.1	0.9	37.0	5.2	7
18	Lagrande	53.53	-76.56	2.9	0.2	19.9	5.9	9
19	Lemoine	49.79	-74.03	3.1	1.0	33.0	9.7	7
20	Matagami	49.72	-77.74	3.5	0.1	37.7	9.9	3, 4, 8
21	Matoush	52.00	-72.09	5.5	2.3	44.8	6.5	10
22	Poste Lemoyne	53.46	-75.21	2.6	0.4	27.1	9.6	9
25	Selbaie	49.82	-78.96	4.9	0.5	47.0	8.5	5
27	Tortigny	50.73	-74.85	2.7	0.2	32.5	10.7	7
			Average	**3.4**	**0.6**	**32.1**	**8.5**	
Churchill Province								
23	Raglan	61.70	-73.58	2.9	0.1	30.8	11.7	9
28	Asbestos Hill	61.81	-73.97	3.2	0.6	38.0	12.0	1, 2
			Average	**3.0**	**0.4**	**34.4**	**11.8**	

[1]Taylor and Judge, 1979; [2]Drury, 1985; [3]Mareschal et al., 1989; [4]Pinet et al., 1991; [5]Guillou et al., 1994; [6]Guillou-Frottier et al., 1995; [7]Mareschal et al., 2000; [8]Perry et al., 2006; [9]Lévy et al., 2010; [10]Jaupart et al., 2014.

3.3 Thermal conductivity of rocks

Thermal conductivity of host rock can vary by as much as a factor of two to three for any given rock type. This is due to the natural variation of a rock's mineral content and porosity as well as to several physical and diagenetic factors. Clauser and Huenges (1995) studied statistical quantities and investigated the variation of thermal conductivity into the four basic groups characterizing the conditions prevailing for rock formation, deposition or metamorphism: 1) sedimentary, 2) volcanic, 3) plutonic and 4) metamorphic (Figure 6 and Table 2).

The factors controlling thermal conductivity of sedimentary rocks are porosity and origin of the sediments (Figure 6). Clauser and Huenges (1995) distinguished two types of sediments: chemical sediments, mainly formed by precipitation of dissolved minerals or by compaction of organic material, and physical sediments, formed by the compaction and cementation of elastic material. Chemical sediments include limestone, coal, dolomite, hematite, chert, anhydrite, gypsum, rock salt, and sylvinite. Low porosity (< 30 %) physical sedimentary rocks are shale (including dolomitic, pyritic, and carbonaceous shale), marl, clayey marl, marlstone, conglomerate, tuff-conglomerate, tuffite, breccia, quartz breccia, and sandstone (including limy and quartz sandstone), while high-porosity (> 30 %) sedimentary rocks are from ocean- and lake-bottom sediments. It appears that chemical sediments and low porosity physical sediments have nearly identical frequency distributions, means, and medians. In contrast, high porosity, mainly marine physical sediments, display a distribution which is biased towards low conductivities, with mean and median about half the size of the previous two. This is due to the low-conductivity fill of the void space, which can be either air or water.

Porosity is again the controlling factor on thermal conductivity for volcanic rocks (Figure 6). Mean and median of the high- and low-porosity histograms differ by nearly a factor of two, and the high porosity distribution is clearly skewed towards low conductivities. The high porosity volcanic rocks considered are lava, tuff, tuff breccia, and mid-ocean ridge basalt (MORB). Low porosity volcanic rocks are rhyolite, liparite, trachodolerite, andesite, and basalt (excluding MORB).

Plutonic and metamorphic rocks display a much smaller porosity. Here the dominant mineral phase controls different conductivity distributions. The feldspar content actually determines the nature of the histogram (Figure 6); while rocks with a low feldspar content (< 60 %) seem to define a nearly symmetrical histogram, a high content in feldspar biases the distribution towards low conductivities. Interestingly enough, means and medians for both distributions are nearly identical within the given standard deviation. Rocks with high feldspar content (> 60 %) are commonly syenite (including alkali and nepheline syenite), granosyenite, syenite porphyry, and anorthosite. Lower feldspar content are granite (including alkali granite, plagiogranite, granodiorite, tonalite, quartz monzonite), quartz- and quartz-feldspar-porphyry, diorite (including monzonite), gabbro (including quartz and olivine gabbro), porphyrite dykes (lamprophyre, diabase, quartz dolerite), and ultramafic rocks (pyroxenite, peridotite, lherzolite, hypersthenite, bronzitite, dunite, olivinite, homblendite, cumberlandite).

Metamorphic rocks can be classified according to their quartz content, resulting in a bimodal distribution (Figure 6). While the low conductivity part is made up of rocks with low quartz-content, the high-conductivity portion consists of quartzite only. High quartz content is mostly associated to quartzite for metamorphic rocks. Low quartz content includes quartz-mica schist, gneiss, marble, serpentinite, talc, serpentinized peridotite, hornfels, eclogite, albitite, leptite, schist, slate, phyllite, amphibolite, mylonite and greenstone.

After reviewing rock thermal conductivities, detailed geological units of the Province of Québec (Figure 7) were grouped into rock types presented in Figure 6 and Table 2 to estimate their mean thermal conductivity.

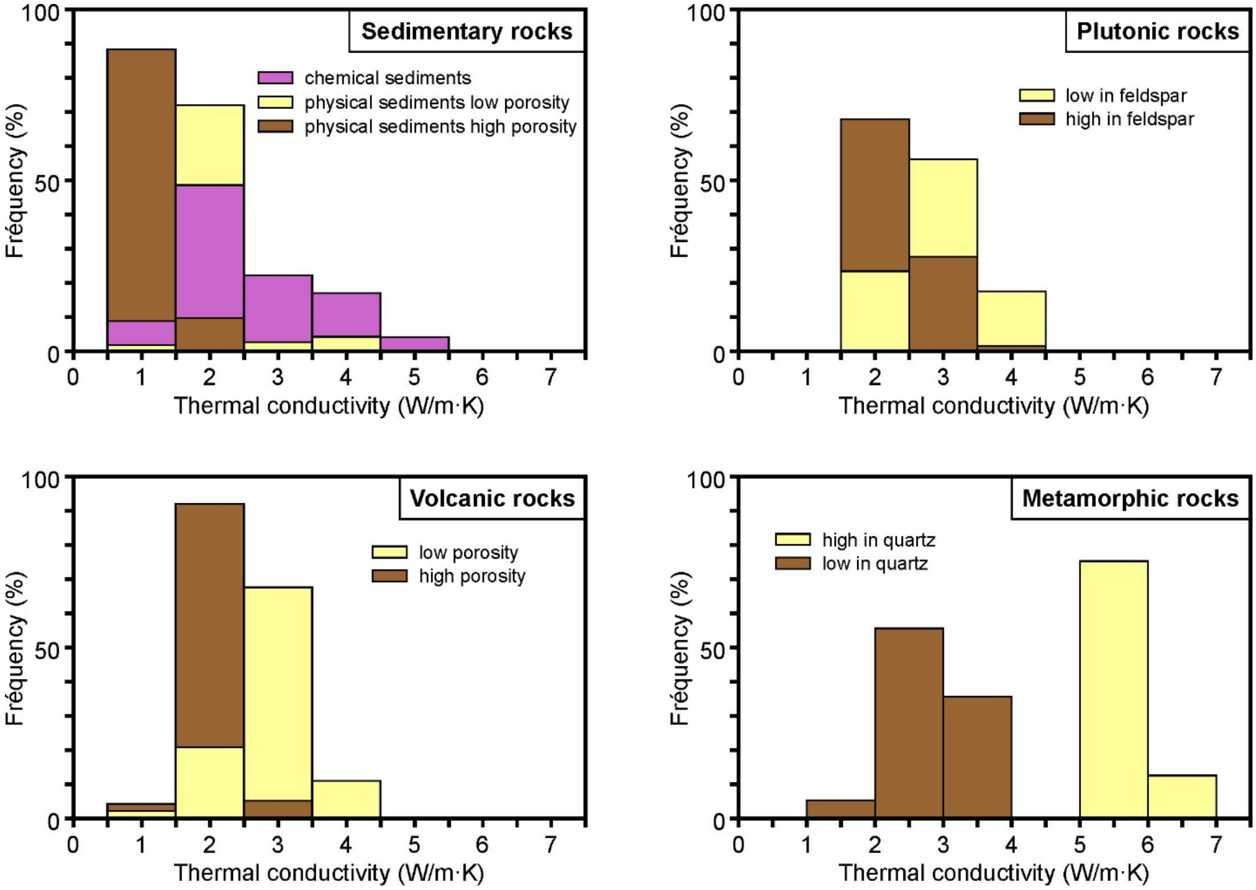

Figure 6: Histograms of thermal conductivity for sedimentary, volcanic, plutonic, and metamorphic rocks. Description of rock types in the text. Note that superposition of different domains results in new pattern styles in diagrams. Modified from Clauser and Huenges (1995).

Table 2: Thermal conductivities values (W/m·K) and statistics for each rock types (from Clauser and Huenges, 1995). n is the number of data, m the median, μ the mean, and σ the standard deviation.

Rock types	Categories	n	μ	m	σ
Sedimentary	Chemical	1 312	2.6	2.2	1.3
Sedimentary	Low porosity	1 880	2.4	2.2	0.6
Sedimentary	High porosity	983	1.2	1.0	0.4
Volcanic	Low porosity	234	2.9	3.2	0.7
Volcanic	High porosity	92	1.9	1.8	0.4
Plutonic	Low feldspar	1 339	3.0	2.9	0.6
Plutonic	High feldspar	303	2.6	2.4	0.4
Metamorphic	High quartz	90	5.8	5.6	0.4
Metamorphic	Low quartz	1 480	2.9	2.9	0.6

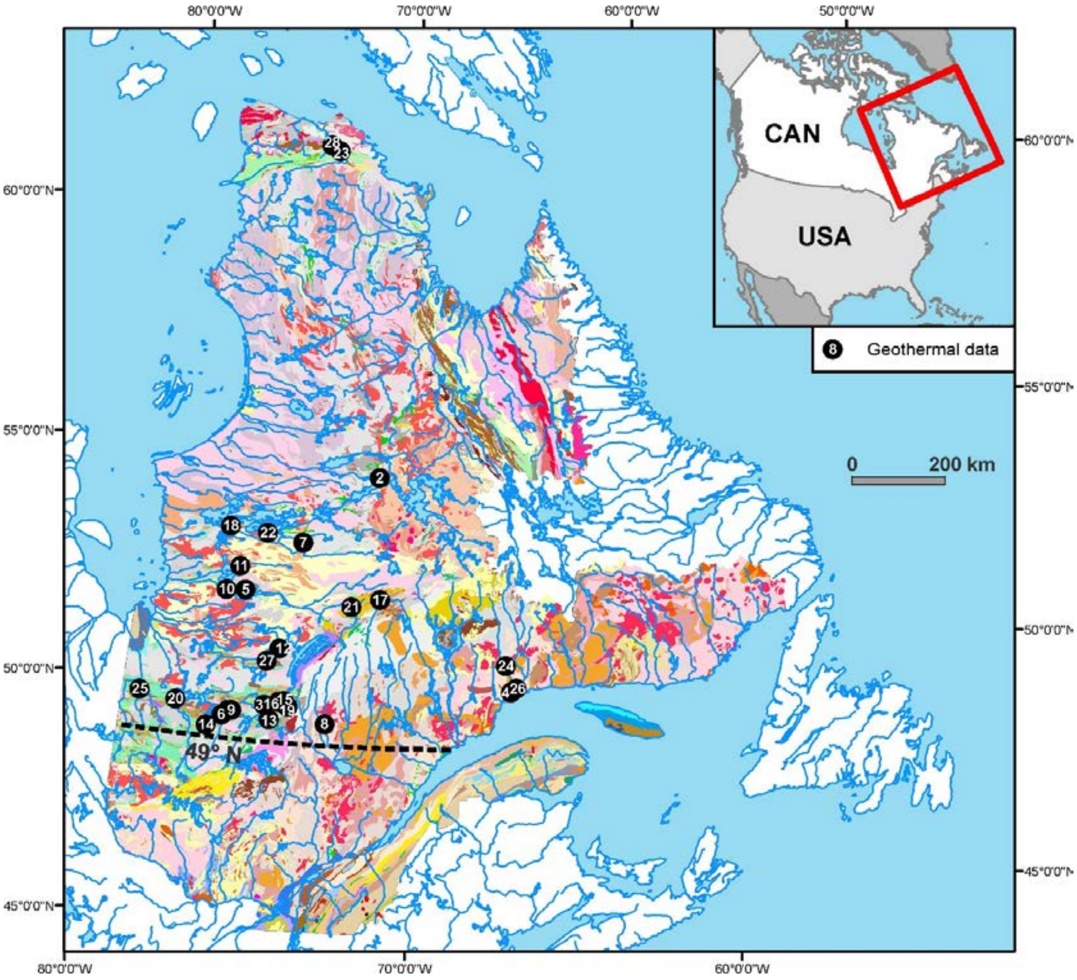

Figure 7: Detailed geology of the Province of Québec and location of geothermal sites of Table 1.

3.4 Best and worst case predictions of temperature at depth

Calculations were performed according to best and worst cases scenarios to anticipate temperature at depth for each of geological province. Surface heat flow and internal heat generation of rocks were assumed constant and equal to average data for each geological province (Table 1) to perform the calculations. The minimum and maximum values of undisturbed ground temperature (T_0; Figure 2) and the host rock thermal conductivity (Figure 8) for each geological province were selected to define the best and worst case scenarios. The parameters used for calculations defining the best and worst case scenarios for each geological province are summarized in Table 3.

Table 3. Geothermal parameters for best and worst case predictions of temperature at depth.

Geological province	T_0 (°C)	Cond. (W/m°C)	Heat flow (W/m^2)	Heat gen. (W/m^3)
Superior min.	-3	5.8	0.0321	6.0E-07
Superior max.	5	2.4	0.0321	6.0E-07
Churchill min.	-4	5.8	0.0344	4.0E-07
Churchill max.	1	2.4	0.0344	4.0E-07
Grenville min.	2	3.0	0.0308	3.0E-07
Grenville max.	6	2.6	0.0308	3.0E-07

4. Results

4.1 Extrapolated temperatures at depth

Undisturbed ground temperatures (T_0) were obtained with the value presented on Figure 2 corresponding with the location of each site. Table 4 presents the calculation results for the temperature (T_{500}, T_{1000}, T_{2000} and T_{5000}) at four different depth (500 m, 1 000 m, 2 000 m and 5 000 m) for each of the twenty-eight sites with geothermal data available in the Northern Québec shown on figures 5 and 7. The extrapolated temperature profiles for each site have been grouped according to their geological province (Figure 8). Sites in the Grenville province have the highest temperature values, with an overall average of 84 °C at 5 km of depth, where a 100 °C is obtained for the site Rivière Sainte-Marguerite (Table 2). Lower subsurface temperatures are obtained in the Superior and Churchill geological provinces, with an average of respectively 50 and 51 °C at 5 km depth.

Direct heat generation without a heat pump is generally feasible for a geothermal resource with a temperature above 40 °C (Geothermal Education Office, 2005). For this reason, the depth (D_{40}) to obtain 40 °C was calculated for each of these sites. A depth around 2 km is obtained for the Grenville geological province, while it takes about twice the depth to reach the same temperature in the Superior and Churchill geological provinces. The depth to reach 40 °C additionally varies with surface temperature and consequently latitude (Figure 9).

Table 4: Extrapolated temperature at depth for well sites from Table 2. T_{500}, T_{1000}, T_{2000} and T_{5000} calculated temperature at 500 m, 1 000 m, 2 000 m and 5 000 m respectively. D_{40} depth to reach 40°C.

Site #	Name	T_0 (°C)	T_{500} (°C)	T_{1000} (°C)	T_{2000} (°C)	T_{5000} (°C)	D_{40} (m)
Grenville Province							
4	Clarke City	5	12	20	34	78	2 411
8	Crevier	5	12	19	33	72	2 620
24	Rivière Sainte-Marguerite	4	14	23	43	100	1 865
26	Sept-Îles	5	13	21	38	87	2 144
	Average	**5**	**13**	**21**	**37**	**84**	**2 260**
Superior Province							
1	Boyvinet	5	10	15	24	52	3 799
2	Camp Coulon	1	5	9	17	37	7 691
3	Chapais	4	7	11	17	37	5 593
5	Clearwater	3	9	16	28	64	3 047
6	Conlagas	5	10	15	24	53	3 737
7	Corvet	2	7	11	21	47	4 404
9	Desmaraisville	5	10	15	25	53	3 734
10	Eastmain River	3	9	14	26	58	3 423
11	Éléonore	2	8	15	27	61	3 326
12	Frotet-Troïlus	4	10	15	26	56	3 576
13	Gamache	5	10	15	24	53	3 630
14	Grevet	5	10	14	24	51	3 852
15	Île Marguerite	4	8	12	20	43	4 681
16	Lac au Doré	4	8	13	21	47	4 243
17	Lac Girafe	2	5	8	14	31	7 588
18	Lagrande	2	5	9	16	35	5 860
19	Lemoine	4	9	14	25	53	3 842
20	Matagami	4	9	15	26	58	3 346
21	Matoush	3	7	11	19	39	6 935
22	Poste Lemoyne	2	7	12	23	52	3 850
25	Selbaie	4	9	14	23	51	3 875
27	Tortigny	4	10	16	28	63	3 074
	Average	**4**	**8**	**13**	**23**	**50**	**4 414**
Churchill Province							
23	Raglan	-4	1	7	17	49	4 200
28	Asbestos Hill	-4	2	8	19	53	3 957
	Average	**-4**	**2**	**7**	**18**	**51**	**4 079**

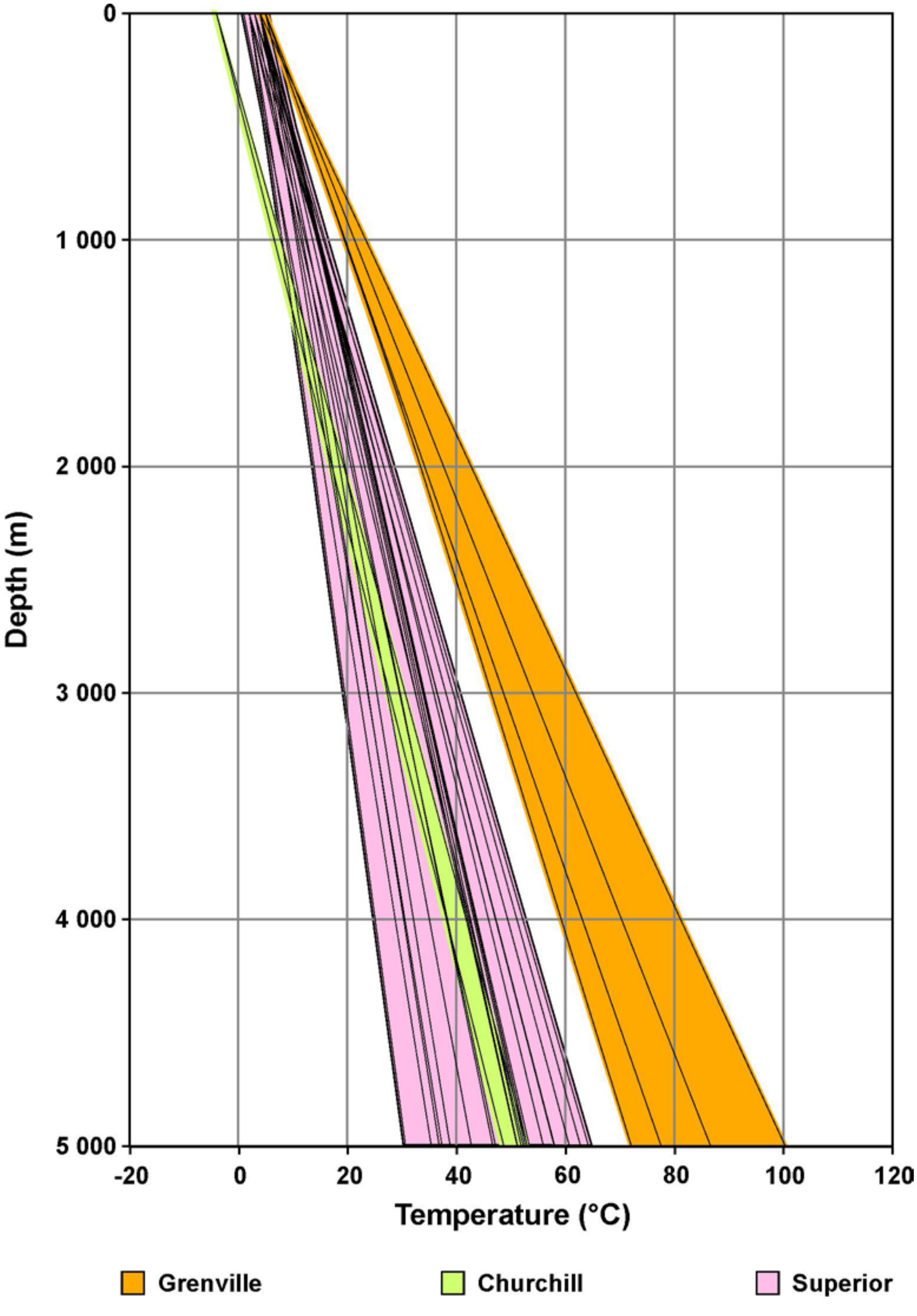

Figure 8: Temperature profiles of Northern well sites from Table 2. See Figure 1 for the geology legend.

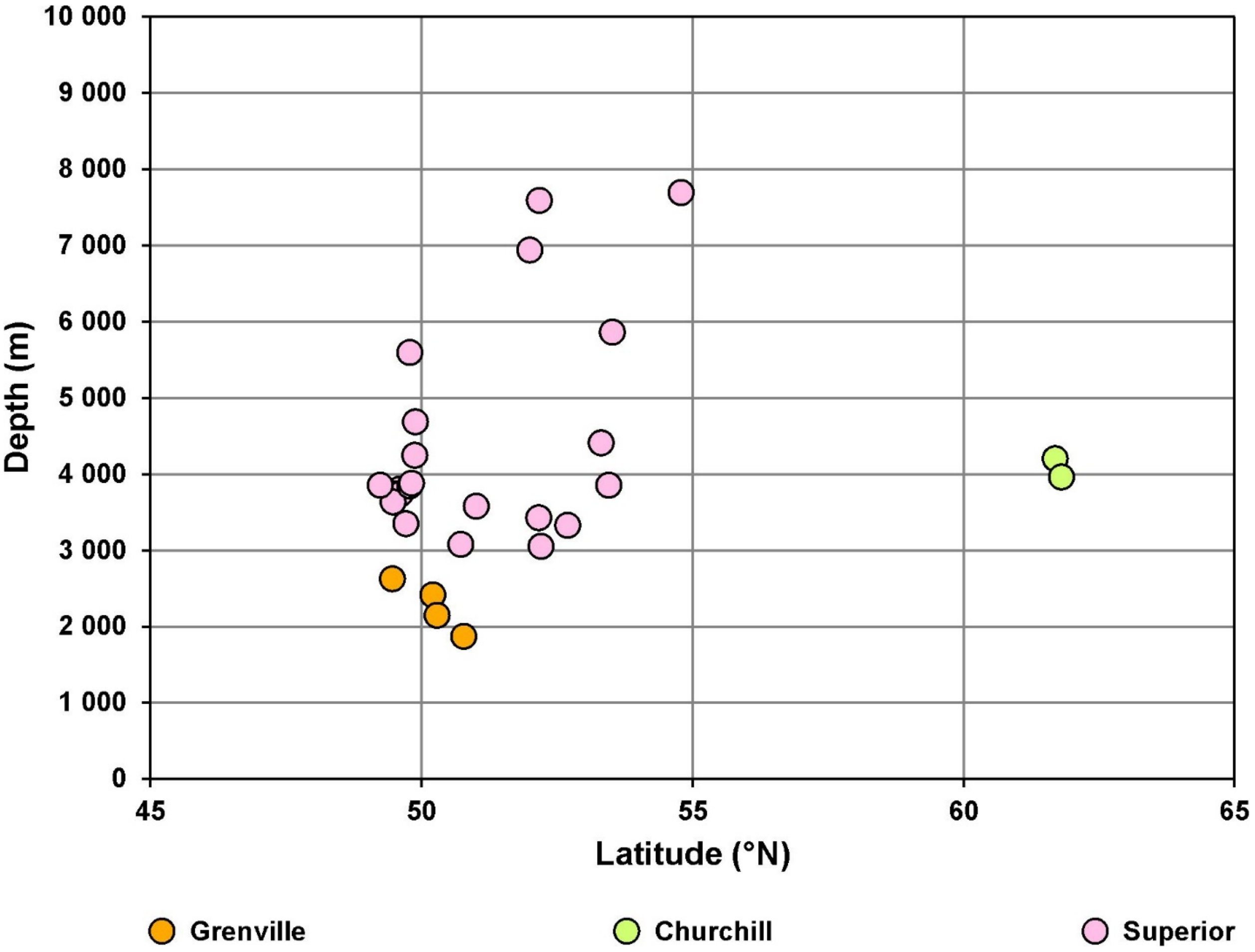

Figure 9: Depth to reach 40 °C for Northern well sites from Table 2.

4.2 Thermal conductivity of rocks

Detailed geological units of the Province of Québec (Figure 7) were grouped into rock types presented in Figure 6 and Table 2 to estimate their mean thermal conductivity. Result of this exercise shows the regional distribution map of the thermal conductivity values near surface throughout the Province of Québec (Figure 10).

4.3 Best and worst predictions of temperature at depth

Results of calculations for the best and worst case scenarios for each geological are shown in Table 5. The best temperature prediction scenario obtained for the Grenville geological province is less than the available data (Table 1). Indeed, the thermal conductivity values for the sites with heat flow evaluation in the Grenville geological province are lower than 2.6 W/m°C (Table 1), which is the lowest value shown on the thermal conductivity distribution map (Figure 10). This is due to the fact that the thermal conductivity value used for the best temperature prediction scenario is the average for plutonic rocks with low-quartz (Table 2), and not the lowest measured value, which can be around 1.5 W/m°C (Figure 6). The temperatures above 100 degrees observed for the "24 Rivière Sainte-Marguerite" site was calculated according to a thermal conductivity value of 1.7 W/m°C or less, which was observed in the upper part of the borehole.

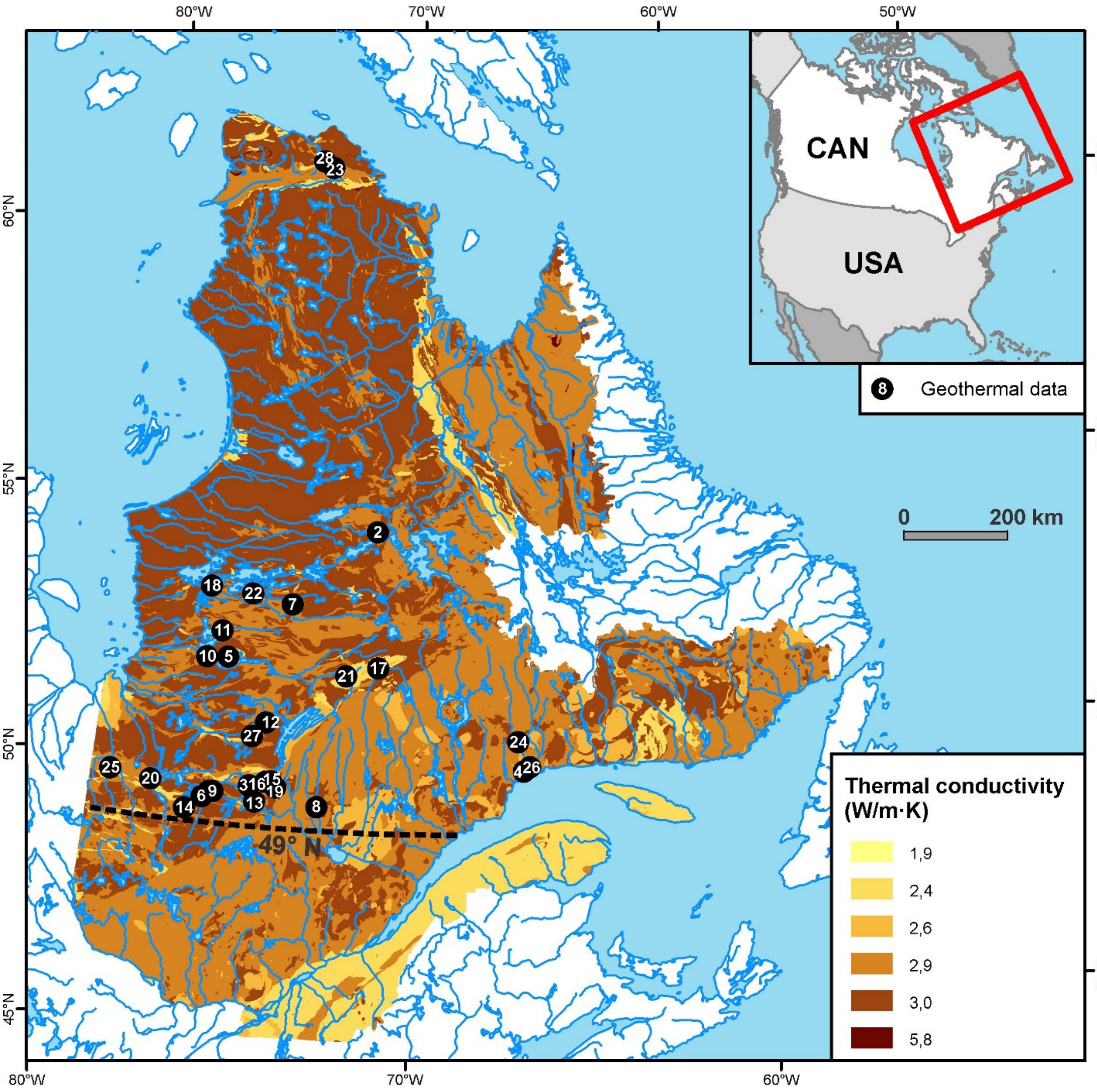

Figure 10: Approximate thermal conductivity distribution of the Province of Québec based on values of Table 2.

Table 5. Extrapolated temperature at depth for best and worst case predictions of temperature at depth for each geological province.

Site name	Gradient (°C/km)	T_0 (°C)	T_{500} (°C)	T_{1000} (°C)	T_{2000} (°C)	T_{5000} (°C)	D_{40} (m)
Superior min.	5.3	-3	0	2	8	23	9 432
Superior max.	12.8	5	12	18	31	69	2 759
Churchill min.	5.8	-4	-1	2	8	25	8 201
Churchill max.	13.9	1	8	15	29	71	2 813
Grenville min.	10.0	2	7	12	22	52	3 701
Grenville max.	11.6	6	12	18	29	64	2 870

5. Discussion and conclusions

As the rocks of the Canadian Shield are very old (2.85-0.97 Ga), their content in radioactive elements is weaker than the same type of younger rocks. This results in rather low values of heat flux throughout the territory of Northern Québec. In this context, the internal heat generation parameter has little influence on the heat flow, as shown in Equation 1. Indeed, when the heat generation values are low, this minimizes the effect of variability among rock types. Thus, the parameter which has the most influence on the resulting geothermal gradient remains the thermal conductivity of the rock. The lower the thermal conductivity value is, the higher the geothermal gradient is. Most part of the Northern Québec has high value of thermal conductivity above 2.9 W/m°C, whereas low thermal conductivity values are usually present over small areas associated to sedimentary and plutonic rocks (Figure 10). In this case, regions with a high thermal conductivity of the ground can be favorable to geothermal heat pump systems, whereas a low thermal conductivity can be appropriate for thermal energy storage systems and direct use of heat from deep wells taping warm aquifers with greater geothermal gradient.

Geothermal energy is used in three main ways: electricity generation, direct heating, and indirect heating and cooling through a geothermal heat pumps (Wu, 2009). The available values (Table 4) show that it would be difficult to generate electricity from geothermal resources in Northern Québec. Indeed, the temperatures reached are exclusively less than 120 degrees for a depth of 5 km. Direct use of heat can be feasible for most of the sites studied at a depth ranging from 2 km to 4 km (Figure 9). Indeed, direct heat production without a heat pump is generally feasible for a geothermal resource with a temperature above 40 °C. For both cases of electricity generation and direct heat use, extraction costs can be important with the expected depth of resources. In the short term, it would be more economical to consider geothermal heat pumps for the Northern Québec, where producing thermal energy is relatively accessible because the drilling depths involved would be less than 1 km. Geothermal heat pump systems can be designed with an operating fluid temperature of 6 to 11 °C colder than the basement temperature in the range of 5 to 10 °C (ASHRAE, 2007). The temperature profiles on Figure 8 demonstrate a viable temperature for geothermal heat pump systems at depth less than 1 000 m. The utilization of heat pumps for space heating would result in energy savings, as electricity or gas is necessary to drive the heat pump cycle. Gas absorption heat pumps can be particularly interesting for areas where electricity is produced from diesel generators, while electric compressor heat pumps can be appropriate if the electricity comes from a renewable energy source. Further work is, however, needed to adapt heat pumps and predict their performances in subarctic to arctic climates.

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