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# Geological, Economical and Environmental Assessment of Combined Geothermal Power and Heat Generation in Québec, Canada

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## ABSTRACT

The south-eastern territory of the province of Québec (Eastern Canada), a region located along the Saint-Lawrence River Valley, including the Gaspésie Peninsula and the Madeleine and Anticosti Islands, has been identified as an interesting area for the future use of deep geothermal energy several decades from now. This region includes a thick 1-5 km sedimentary rock wedge deepening southwest towards the Appalachian disturbed belt front. The deep part of the sedimentary wedge offers the potential to produce geothermal heating and power from the deep aquifers in the future. Relatively elevated heat flow densities in some thermal anomalous areas (i.e. >60 mW/m$^2$) also result in prospects for temperatures above 120°C at about 4 km in the sedimentary aquifers. Additionally, geothermal power and heat production from hot dry deep granites located below the sedimentary cover can also be considered using Enhanced Geothermal Systems (EGS). On the other hand, Northern Québec, a vast territory covering nearly 1.2 million km$^2$ of land located north of the 49$^{th}$ parallel, presents very low mean annual surface temperatures and a relatively low average heat flow density of about 40 mW/m$^2$. This area would require deeper drilling for heat mining, i.e. 80°C at a depth of about 4.5 km. In the medium and long terms, geothermal energy could be feasible in the province of Québec with positive future energy and environmental impacts.

## 1. INTRODUCTION

In Eastern and Northern Canada (Fig. 1), the average geothermal heat flow density is much lower than in Western Canada where younger Cordillera carry more geothermal energy (Majorowicz and Grasby, 2010). This is because large parts of Eastern Canada, including the province of Québec, are located in the geothermal "cold" Canadian Shield, while some are in a "hotter" sedimentary platform related to the Appalachian basins. The heat flow density map shown in Fig. 1 has been developed based on high precision measurements provided by the International Heat Flow Committee (IHFC).

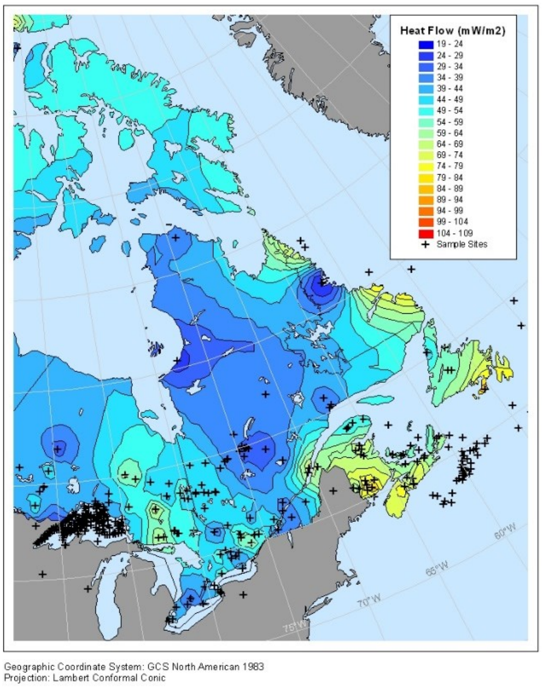


**Figure 1: Heat flow contour map for Eastern Canada based on IHFC (IHFC = International Heat Flow Commission) heat flow density data base.**

Potential areas in Southern and South-Eastern Québec (i.e. St. Lawrence Valley, Gaspé Peninsula and the Magdalen and Anticosti Islands) for power and heat production from deep dry hot rocks with Enhanced Geothermal Systems (EGS) and/or from existing deep aquifers in sedimentary strata have been previously studied by Minea and Majorowicz (2011), Majorowicz and Minea (2012), Minea and Majorowicz (2012) and Majorowicz and Minea (2013). In these areas, mainly located between Montréal, Trois-Rivières, Sherbrooke and Québec City (i.e. the largest population centers of the province), the Gaspésie Peninsula and the offshore islands, we find sedimentary rock formations with a thickness of a few kilometers over the top of an old deep crystalline basement (mainly Grenville). Many oil and gas exploration wells were drilled there in the past. In the south-eastern (Fig. 2) part of the sedimentary cover (yellow shaded areas of the platform, Fig. 2), some 2-5 km thick sediments exist as evidenced from the interpretation of several seismic profiles running orthogonal to the strike of the St. Lawrence River Valley (MRNQ seismic profiles - 2001, 2002, 2003). The first geothermal potential assessment has shown that the heat could be exploited through artificially created deep heat exchangers or by direct tapping of the saline fluids existing within the Paleozoic rock aquifers. The choice of the heat extraction technique depends on geological factors (sedimentary vs. crystalline rocks) and the thermal potential of the available heat.

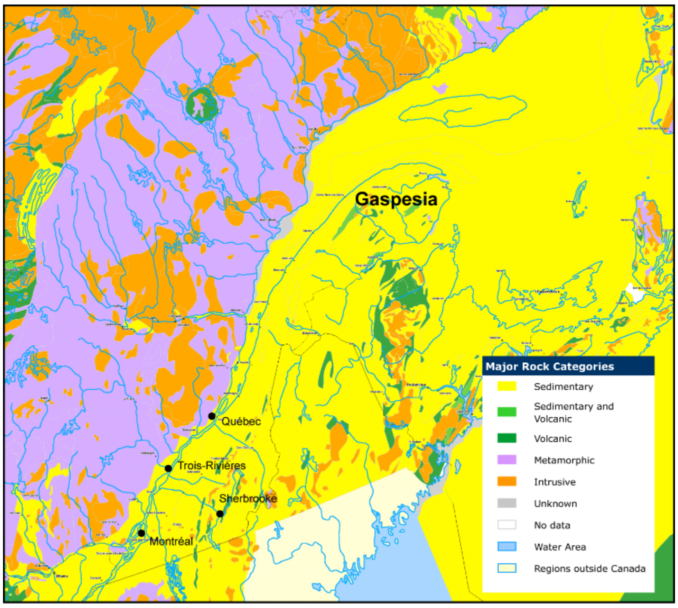


**Figure 2: Major rock types in Québec, Eastern Canada. Note: Sedimentary rocks are mainly found in South-Eastern Québec and the crystalline (metamorphic and intrusive) rocks in the Precambrian area in the north-eastern part of the province (modified from the Geological Survey of Canada web site map 2007).**

In the case of deep dry hot rocks, artificially created Enhanced Geothermal Systems (EGS) (Tester et al., 2006) may be the only way to tap into the high temperature heat >120 °C (preferably, 150 °C) available in the crystalline basement rocks. To achieve this, a thermal carrier fluid (water, etc.) needs to be pumped into a closed loop system through the underground reservoir to extract the geothermal heat and through the power plant boiler, prior to being re-injected in the ground. In the second scenario, direct geothermal heat extraction could be performed from existing deep sedimentary aquifers like those in the Trenton, Black River and Beekman Groups, respectively, as well as in the deeper Potsdam Group (Dietrich et al., 2011; Minea and Majorowicz, 2012; Majorowicz and Minea, 2012). Good geothermal conditions have also been found in Paleozoic formations (Lavoie et al., 2009) in the Gaspésie Peninsula (Majorowicz and Minea, 2013). The city of Sherbrooke (see Fig. 2 for location) is in an area which has deep aquifers in deep sediments able to support the production of direct heating or small EGS power from the deepest aquifers. The cities of Montréal, Trois-Rivières and Québec are located along the St. Lawrence River Valley, north of the thinner sedimentary cover (Fig. 2) which extends south-easterly towards Sherbrooke. As can be seen in Fig. 2, the Northern Québec region is located mainly in Precambrian metamorphic, intrusive and old volcanic rocks, with several wells drilled for mineral exploration.

This paper analyzes in greater detail the geothermal energy potential of the whole Québec comparing the potential of both the Southern and Northern regions, as well as the economics and $CO_2$ offsets of deep geothermal systems for the potential production of power and heat. One of the most important challenges is to predict the drilling depth required to reach the temperatures needed for power or heat production. This paper focuses on two examples at temperatures of 80°C and 120°C, i.e. the lowest temperatures suitable today for heat and power production at reasonable drilling depths.

## 2. HOW DEEP SHOULD THE DRILLING BE PERFORMED TO REACH TEMPERATURES TECHNICALLY USEABLE FOR POWER GENERATION?

To estimate the temperatures to depth of sediments for an assumed heat generation value (generally, lower than 1 W/m$^3$), knowledge of heat flow density (Fig. 1) and thermal conductivity (Fig. 3) is needed. At an assumed 1 μW/m$^3$ heat generation value, heat flow density decreases with depth in small increments of 1mW/m$^2$/km. Because there are no direct thermal conductivity measurements for Québec sediments, average thermal conductivity values have been calculated for the major formation groups as shown in Fig. 3. The thermal conductivity of shale has been kept constant with depth according to evidence given in Blackwell et al. (1991), and it has been assumed that porosity is decreasing with depth exponentially.

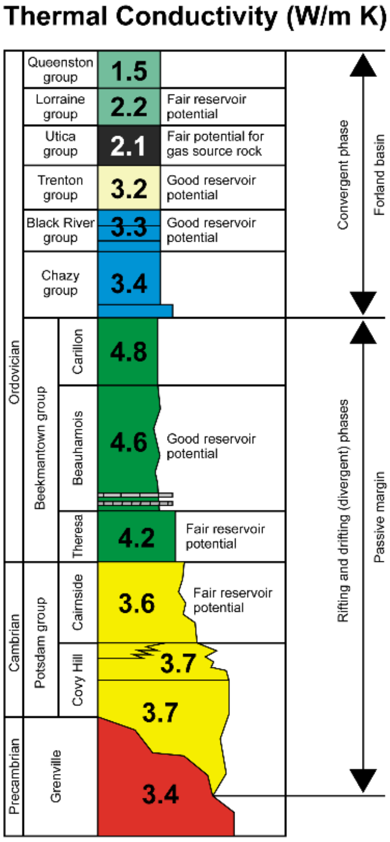


**Figure 3: Thermal conductivity (W/mK) estimates and major fair to good aquifers in the Southern Québec sedimentary area.**

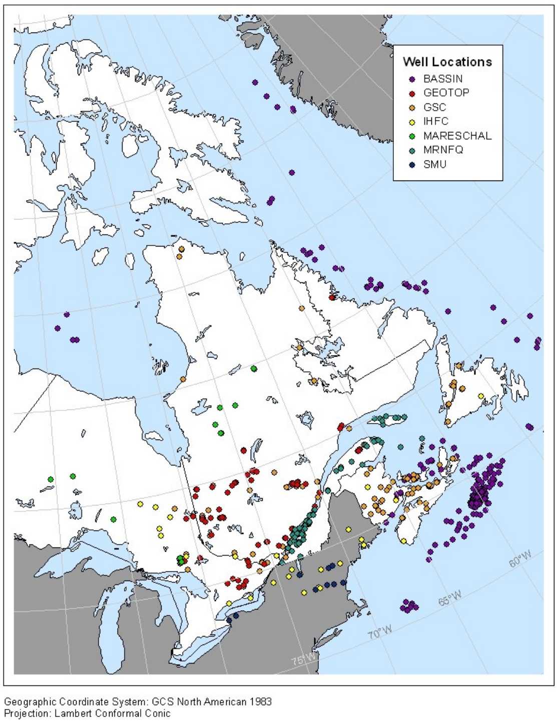


**Figure 4: Well locations with BHT data used to predict temperature-to-depth maps.**

Temperatures to depth have been predicted using the BHT data available from deep wells (Fig. 4). This data consists in industrial BHT and drill stem test (DST), which include single depth records temperatures. Such a thermal data (Minea and Majorowicz,

2011) is less precise than high precision temperature logs in equilibrium wells, as listed in the IHFC data base. The map shown in Fig.4 includes additional locations from IHFC temperature data base from deep exploratory wells in Québec.

Predictions from the low and high heat flow densities likely to occur in Northern and Southern Québec respectively show that the range of high and low temperature gradients is very large (Fig. 5). The depth map to a temperature of 120°C (Fig. 7) shows that in the high heat flow density area from Trois-Rivières to Québec City and towards Sherbrooke, temperatures >120°C can be reached in the sediments of the deepest laying aquifers of the Potsdam group at a 4-4.5 km depth.

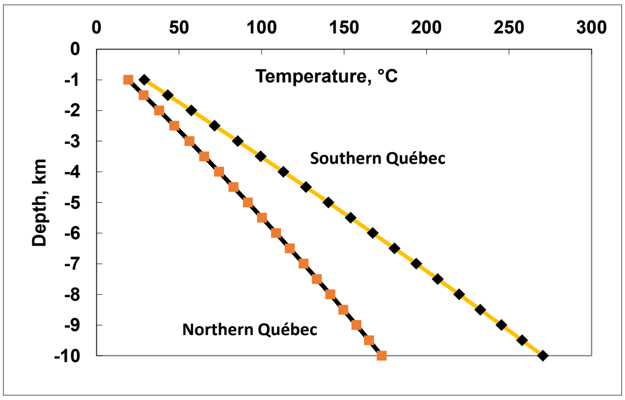


**Figure 5: Temperature-to-depth predictions for high heat flow in Southern Québec and low heat flow in Northern Québec (75 mW/m$^2$ and 40 mW/m$^2$+1 S.D., respectively) for an assumed heat generation of 1.1 W/m$^3$ and mean thermal conductivity of 2.6 W/m K (S.D. – standard deviation).**

Things are different in Northern Québec where the potential geothermal power production areas are too deep to be drilled economically. Northern Québec is in fact a large geographical area with a low average heat flow of about 40 mW/m$^2$ (Fig. 1) and a low geothermal gradient (around 15°C/km). Temperatures >120°C may be possibly reached, but at significant drilling depths (>8-9 km) in most places. However, the cost of drilling 8-10 km wells would be quite impossible to support at today's cost rates.

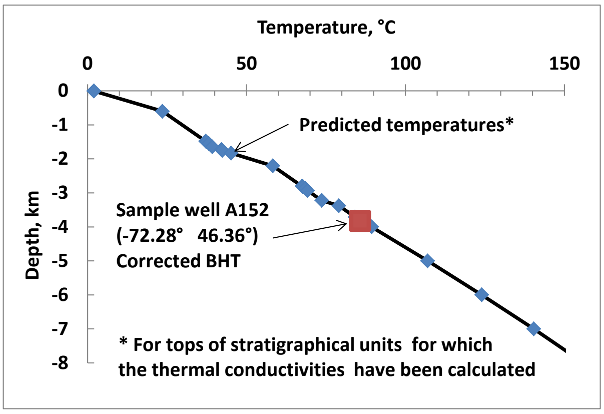


**Figure 6: Detailed temperature-to-depth predictions for sample well A152 located in the St. Lawrence area from estimated heat flow density (52 MW/m$^2$) and thermal conductivity model based on litho-stratigraphic section conductivities shown in Fig. 3. Note: The temperature-to-depth curve has been constrained by measured and corrected BHT. In this case, the measured and corrected temperature of 86°C is at a 3.8 km depth.**

The corrected temperature data, heat flow densities, heat generation and thermal conductivity model from Majorowicz and Minea (2012, 2013) has been used to predict the possible temperature depth range for the upper 10 km layer through the sedimentary column and crystalline rocks, and surface temperature of 0°C (Fig. 5). It can be seen that at an economically reasonable drilling depth of about 4.5 km, temperatures of 80-120°C would be reached in the worst and best case scenarios for the low and high heat flow densities, respectively. Fig. 6 shows that when more information is given for the sedimentary rock thermal conductivity model (Fig. 3), more detailed temperature predictions are possible. The new contour map showing depths to 120°C (Fig. 7) is an approximation as data distribution (see locations in Fig. 4) is uneven and data was extrapolated between the sparse wells located tens of kilometers apart in the northern low data density area.

## 3. IS IT ECONOMICAL?

In order to assess the potential amount of heat that could be extracted from deep geothermal reservoirs, the following assumptions have been made (see Table 1): (i) two temperature limits, i.e. minimum of 80°C and maximum of 120°C (preferably, 150°C), are taken as examples for the extreme geothermal conditions available (see Fig. 7 for the predicted depths to reach 120°C); (ii) heat at such relatively low temperatures can be used for industrial and/or domestic heating as well as for producing electrical power if sufficient geothermal fluid flow rates are achievable; (iii) geothermal fluid flow rates may vary between a minimum of 10 kg/s and a maximum of 80 kg/s; (iv) electrical power could be generated at conventional binary cycles involving one production and one (or more) reinjection well(s); (v) the temperature of the re-injected fluid is 40°C, a standard value assumed for presently available power generation technologies (Tester et al., 2006); (vi) 50% or more (up to 1 MWe) of the electrical power generated could be required for pumping the geothermal fluid through the deep geothermal reservoir between the production and re-injection wells.

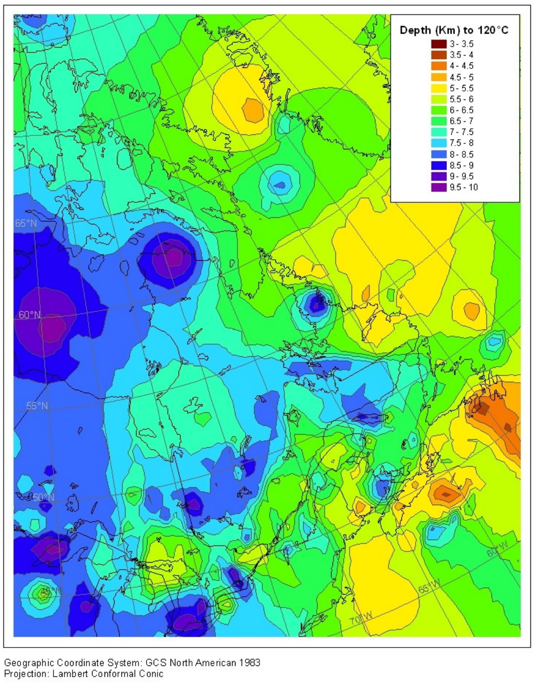


**Figure 7: New contour map of predicted drilling depths to potentially reach 120°C in Eastern and Northern Canada, including the province of Québec, and part of the United States.**

**Table 1: Basic parameters used to assess the potential amount of heat to be extracted from deep geothermal reservoirs.**

| Parameter | Range | Unit |
|---|---|---|
| Geothermal fluid temperature | 80 & 120 | °C |
| Specific heat capacity of geothermal fluid | 4186 | J/kgK |
| Drop off (reinjection) temperature | 40 | °C |
| Geothermal flow rate | 10 to 80 | kg/s |

For costs calculations, additional assumptions have been made: (i) the gross electrical power needed to run pumps (production and re-injection) is 1 MWe; (ii) the technical life of the geothermal sites varies from 10 to 30 years; (iii) the major overnight investment costs are well costs, which depend on depth drilled, drilling and casing which can be recovered over the system assumed lifetime depending on the resource and the management of geothermal fluid flows; (iv) additional costs of fracture enhancement and installation works have been assumed at 0.5 CanM$ per site; (v) in the case of deeper EGS applications, the drilling, fracturing, system bounding and geothermal fluid circulation costs have been approximated based on a statistical compilation performed for several geothermal, oil and natural gas prospective wells by Tester et al. (2006). A statistical function on drilling-cost with depth for EGS developments was constructed (see equation 1 bellow) and assumed in these calculations. Previous estimates for drilling a single EGS well needed to be adjusted to current prices. The equation used to define the cost (Can$) of single well drilling to depth z (km) is:

$$COST = 7*10^{-11}z^3 + 4*10^{-7}z^2 + 0.0022z + 1.4 \quad (1)$$

The first results are shown in Fig. 8, which presents an estimation of the specific costs (expressed in Can$/GJ) of the geothermal heat recovered as a function of the geothermal fluid flow rate and temperatures. The system lifetimes have been assumed at 10 years for Northern Québec, and 10 years and 30 years for Southern Québec. In Northern Québec, the maximum temperature of the geothermal sources is 80°C (the most optimistic case, see Fig. 5), while in Southern Québec it may vary from 80°C to120°C at reasonable depths. It should be noted that the estimated costs of geothermal heat at both minimum and maximum temperatures (80°C and 120°C, respectively) are not competitive with the currently low prices of natural gas used for space and/or industrial heating at low flow rates.

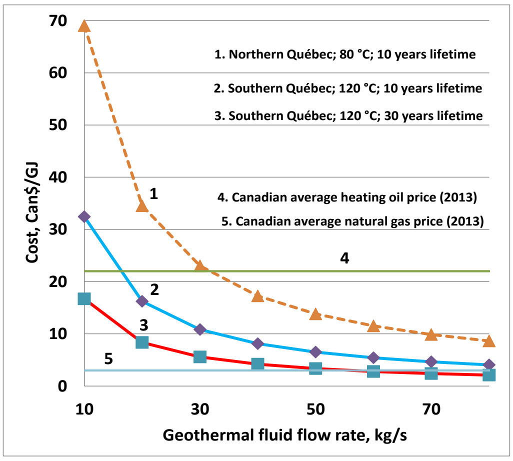


**Figure 8: Specific costs of geothermal heat recovered as a function of geothermal fluid flow rate and temperatures, and system lifetime (Note: Reference lines showing prices for Canada are from http://www.nrcan.gc.ca/energy/natural-gas/12432).**

With geothermal fluid eventually available at 80°C in Northern Québec, power generation at economical heat-to-electricity conversion efficiencies and reasonable flow rates is not achievable today. A similar conclusion could be concerning the use of geothermal heat for district and/or industrial heating purposes. By assuming, for example, a geothermal fluid flow rate of 30 kg/s and production and re-injection temperatures of 80°C and 40 °C, respectively, the maximum thermal power recovered would be only 0.5 thermal MW, while substantial electrical power (at least 1 MWe) may be required to operate the submerged and surface auxiliary circulating pumps. However, such a scenario should be competitive with the currently high heating fuel prices, such as diesel fuel and propane, which are shipped over very long distances to isolated populated municipalities in Northern Québec.

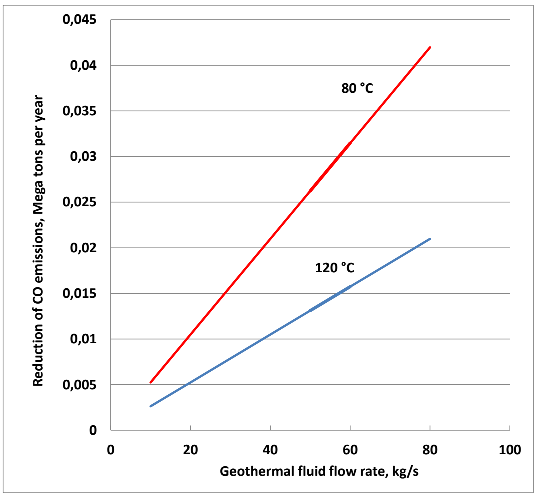


**Figure 9: Theoretical reduction of CO2 emissions based on energy production replaced by a two-well EGS geothermal system.**

In Southern Québec, where deep geothermal heat at temperatures >120°C could be found at depths over 6.5-7 km, electrical power generation probabilities look more optimistic. In this region, with geothermal flow rates of 30 to 60 kg/s, enough gross electrical power could be produced to supply the electrical power required for circulating pumps. On the other hand, in Southern Québec, geothermal heat production for district and/or industrial heating only seems much more competitive at geothermal fluid flow rates <20 kg/s (Fig. 8).

Finally, as can be seen in Fig. 9, the use of deep geothermal heat for heating purposes could significantly reduce greenhouse gas emissions in the form of $CO_2$. For example, geothermal heat production at 120°C with a very optimistic flow rate of 80 kg/s and a two-well geothermal system could reduce $CO_2$ emissions by 0.04 megatons per year. If, for example, 200 similar installations were implemented in the future, annual reductions of $CO_2$ emissions of up to 10% could be achieved compared to conventional energy sources (e.g. heating oil, natural gas or diesel fuel).

## REFERENCES

Blackwell, D.D., Beardsmore, G.R., Nihimori, R.K., and McMullen, R.J.: High resolution temperature logs in a petroleum setting: Examples and applications, *Basin Analysis: Computer Applications in the Earth Sciences* ed A Forster and D Merriam, New York: Kluwer/Plenum (1991), 1–34.

Dietrich, J., Lavoie, D., Hanningan, P., Pinet, N., Castonguay, S., Giles, P., and Hamblin, A.: Geological setting and resource potential of conventional petroleum plays in Paleozoic basins in eastern Canada, *Bulletin of Canadian Petroleum Geology*, **59**, (2011), 54–84.

Geological Survey of Canada: Geological map of Canada, (2007), ftp://ftp.mrnf.gouv.qc.ca/public/Geologie/documentsRP/Geological_map.pdf.

Lavoie, D., Pinet, N., Dietrich, J., Hannigan, P., Castonguay, S., Hamblin, A.P., and Giles, P.: Petroleum resource assessment, Paleozoic successions of the St. Lawrence Platform and Appalachians of eastern Canada, *Geological Survey of Canada, Open File* 6174, (2009), 273.

Majorowicz, J.A., Grasby, S.: Heat flow, depth–temperature variations and stored thermal energy for enhanced geothermal systems in Canada, *IOP J. Geoph. Eng.*, **48**, (2010), 232-241.

Majorowicz, J.A., Minea, V.: Geothermal anomalies in the Gaspésie Peninsula and the Madeleine Islands, Québec, *GRC Transactions*, **36**, (2013), 295-300.

Majorowicz, J.A., Minea, V.: Geothermal energy potential in the St-Lawrence River area, Quebec, Canada, *Geothermics,* **43** (2012), 25– 36.

Majorowicz, J.A.: Permafrost at the ice base of recent Pleistocene glaciations – inferences from borehole temperature profiles, *Bulletin of Geography-Physical Geography Series*, **5**, (2012,), 7-28, DOI: 10.2478/v10250-012-0001-x.

Minea V., Majorowicz, J.A. Preliminary: Assessment of Deep Geothermal Resources in Trois-Rivières Area, Québec, *GRC Transactions*, **36**, (2012), 709-715.

Minea, V., Majorowicz, J.A.: Assessment of Enhanced Geothermal Systems Potential in Québec, Canada, *AAPG/SPE/SEG Hedberg Research Conference Enhanced Geothermal Systems*, Napa, California, (2011), March, 14-18.

Tester, J.W., et al.: The Future of Geothermal Energy - The Impact of Enhanced Geothermal Systems on the United States in the 21st Century, *MIT Press*, 2006.