Thermohydraulic characterization of Charlevoix crater rocks

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ABSTRACT

Geothermal resources offer an energy alternative to reduce carbon emissions. However, exploration remains challenging for fractured bedrock. Insulating rocks in impact crater areas are known targets for geothermal exploration. A potentially elevated geothermal gradient may be found in the St-Urbain anorthosite in Charlevoix (Quebec). This work aims to characterize the thermohydraulic properties of the main geological formations to better understand heat transfer mechanisms. Rock properties were evaluated using an infrared scanner and a transient gas porosimeter and permeameter for artificially fractured samples. In the field, permeability was evaluated by the Porchet method. Anorthosite fractured samples showed a geometric average permeability of 4.1×10^{-12} cm^2, which is smaller than the value inferred in the field (9.6×10^{-11} cm^2). Artificially fractured charnockite showed an increase in permeability by 3 orders of magnitude. Advection can be expected as a heat transfer mechanism in such fractured rocks.

RÉSUMÉ

Les ressources géothermiques offrent une alternative énergétique pour réduire les émissions de carbone. Cependant, l'exploration reste difficile dans un socle rocheux fracturé. Les roches isolantes dans les zones de cratères d'impact sont des cibles connues pour l'exploration géothermique. Un gradient géothermique potentiellement élevé pourrait être trouvé au sein de l'anorthosite de St-Urbain (Charlevoix). Ce travail a pour objectif de caractériser les propriétés thermohydrauliques des principales formations géologiques afin de mieux comprendre les mécanismes de transfert de chaleur. Ces propriétés ont été évaluées avec un scanner infrarouge et un perméamètre et porosimètre pour des échantillons artificiellement fracturés. Sur le terrain, la perméabilité a été évaluée par la méthode de Porchet. Les échantillons fracturés d'anorthosite ont montré une moyenne géométrique de 4.1×10^{-12} cm^2, soit inférieure à la perméabilité évaluée sur le terrain (9.6×10^{-11} cm^2). Les charnockites artificiellement fracturées ont vu augmenter leur perméabilité de 3 ordres de grandeur. L'advection peut être un mécanisme de transfert thermique dans ces roches de socle fracturées.

1. INTRODUCTION

Rising energy costs, the requirement to reduce greenhouse gas emissions, and the scarcity of resources are driving the need to diversify energy grids with alternatives that have a lower environmental impact and are sustainable over time, such as geothermal energy (Allen et al., 2000). Deep geothermal resources are one of the renewable and viable options to reduce greenhouse gas emissions and mitigate climate change (Hecht et al., 2012; Paulillo et al., 2020). However, their use remains challenging, especially for hot fluids hosted in fractured basement rocks lacking primary porosity (Rejeki et al., 2005).

Geothermal energy in Canada is mainly used for two applications: heating and cooling of buildings with geothermal heat pumps and bathing at hot springs (Raymond et al., 2015). Insulating rocks in meteorite impact craters are known targets for geothermal exploration (Henkel et al., 2005), and the St-Urbain anorthosite in Charlevoix may offer an appropriate setting to find a geothermal gradient that is more elevated than in the surrounding rocks (Abramov & Kring, 2004).

The area of the Charlevoix crater has been studied since the mid-1990s to understand the impact of the meteorite that formed the Charlevoix's Astrobleme about 400 million years ago (Buchbinder et al., 1988; Mareschal & Chouteau, 1990; Lamontagne et al., 2000; Lemieux et al., 2003). However, no study has yet focused on its geothermal potential. In 2015, the University of Quebec in Chicoutimi conducted a characterization of groundwater as part of a knowledge acquisition program in the Charlevoix and Haute-Côte-Nord areas (CERM / UQAC, 2015).

Regional faults such as the St. Lawrence fault were reactivated under the meteorite impact (Lemieux et al., 2001), causing an intense fracturing. The presence of insulating rocks such as the Saint-Urbain anorthosite could offer a favorable setting to

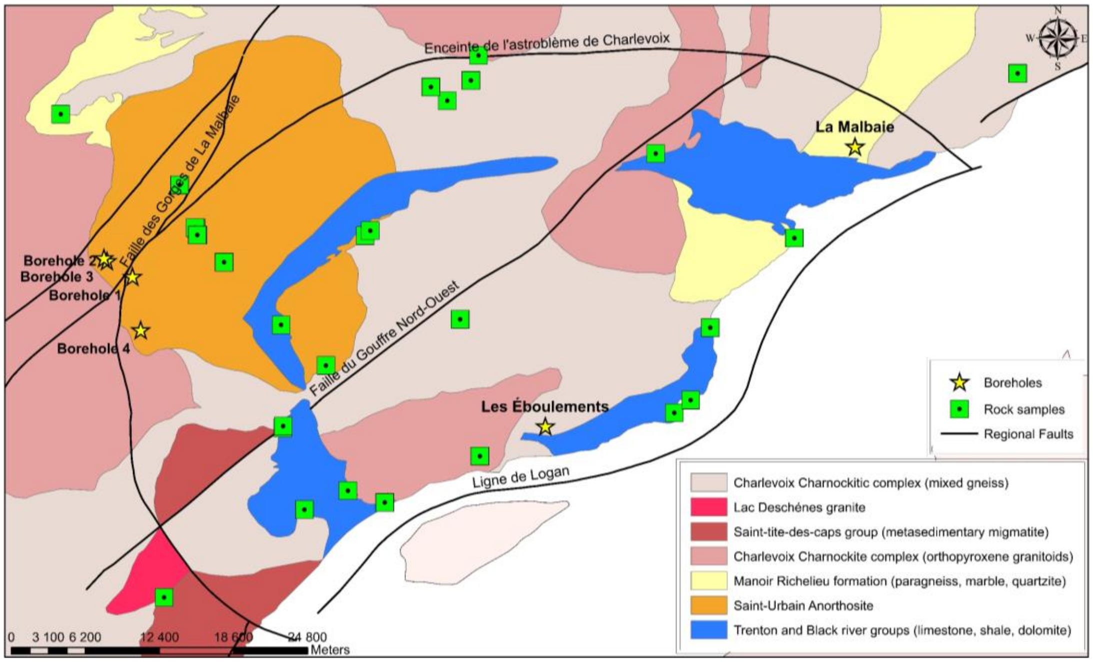

Figure 1. Geological context of the Charlevoix region based on the cartographic information from SIGEOM (Gouvernement du Québec, 2012), indicating locations of collected rock samples and fracture density measurements.

find a geothermal gradient higher than what was previously measured in the surrounding basement rocks in La Malbaie and the Mont des Éboulements (Guillou-Frottier et al., 1995), potentially providing attractive conditions to develop deep geothermal resources. A full assessment of the bedrock characteristics in the area for deep geothermal resources exploration is of economic importance. Knowledge about thermal and hydraulic properties of rocks and fracture systems are critical parameters for the characterization of geothermal systems, allowing to assess the efficiency of flow and heat transfer mechanisms (Bauer et al., 2017). In the Charlevoix region, if groundwater flow systems and thermal properties of the rocks are favorable, deep geothermal resources could be used for direct applications with 1 to 3 km deep wells producing hot water for the agriculture and food transformation industry, both important activities in the area.

Thus, this work aimed to characterize the thermal and hydraulic properties of the main geological units in the Charlevoix crater region to better understand heat transfer mechanisms in the field. Analysis was also made in the laboratory on samples with and without fractures in addition to field permeability tests in boreholes.

2. GEOLOGICAL CONTEXT

The Charlevoix crater is situated 100 km northwest of Quebec City. This region has several well-developed supracrustal faults mostly oriented NW-SE and NE-SW, overlaid by features typical of deformation conditions that have historically been interpreted as a meteorite impact (Rondot, 1968).

The gneisso-granitic rocks, the charnockite gneiss and massive rocks of the Charlevoix charnockite complex, and the anorthosite mass of St-Urbain constitute 95 % of the bedrock in the region (Robertson, 1968; Figure 1). The other 5 % corresponds to sedimentary units of the St. Lawrence Platform (Lemieux et al., 2001).

The gneisso-granitic rocks are present in the eastern part of the region with a general eastward dip. They include the paragneisses of the La Malbaie metasedimentary group, migmatites, and granites, as well as the Cap-aux-Oies granite (Rondot, 1968). The charnockitic rocks to the northwest of the crater are found with some enclaves of garnet gneiss. In the northwest region these same enclaves are found with sillimanite, as well as gneissic granodioritic rocks with hypersthene and augite, and massive rocks have large crystals of mesopertite and pyroxene, with plagioclase or quartz (Rondot, 1968). The St-Urbain anorthositic mass located to the northwest of the crater appear as semi-granular rocks or rocks with large crystals of several tens of centimeters in size. One third of this mass is at the altitude of a plateau, up to 900 m, and it is cut by valleys. The other part is flat and at an average altitude of 300 m. At the east of Baie-Saint-Paul and near the Mont des Eboulements are small, isolated outcrops of anorthosite (Rondot, 1968).

3. METHODOLOGY

Previous field work has been conducted in 2019 (Velez et al., 2020), where *in situ* permeability measurements have been made and rock samples have been collected in outcrops of both formations and previously drilled wells (Table 1). A total of 4 holes that were drilled for mineral exploration in the St-Urbain anorthosite were sampled (Figure 1). Two are located outside the crater area, FH-01 and FH-02, and have a depth of 291 and 330 m, respectively; and two others are inside the crater area, FH-03 and FH-04, and have a depth of 351 and 228 m, respectively. Petrophysical properties of rock samples were measured at the Laboratoire ouvert de géothermie of the Institut national de la recherche scientifique in Quebec City (Raymond et al., 2017).

Table 1. List of rock samples collected for laboratory measurements.

Sample ID	Lithology	Location
C9, C11, C12, C20. C21	Anorthosite	Outcrop
FH-01, FH-02, FH-03, FH-04	Anorthosite	Well
C1, C2, C3, C4, C6, C8, C16, C19, C22, C23, C24, C25, C26, C27, C28	Charnockite	Outcrop

3.1. Thermal properties assessment

3.1.1. Thermal conductivity and diffusivity assessment

All samples taken from outcrops were prepared by cutting a flat surface on one of their side and oven dried at 110°C for 72 h. The flat surface was painted black to ensure optimal absorption of infrared waves during infrared scanning measurements (Popov et al., 2016). The standard samples, fused quartz and titanium alloy recommended for natural materials, were chosen, and left at room temperature for 24h together with the samples to ensure reaching thermal equilibrium. The thermal conductivity scanner was calibrated, and measurements were started in combined thermal conductivity and thermal diffusivity mode. Samples extracted from the well went through the same process except that during the measurements, thin flat 3D printed plastic support were placed on the scanning platform to match their level with the cylindrical samples (Popov et al., 2016).

3.1.2. Internal heat generation

Heat flux at the crust surface can be affected by the heat generated from the decay of radioactive elements *A* (μW m^{-3}), which was estimated with Eq. 1 (Bücker & Rybach, 1996) using geochemical analysis of rock samples:

$$A = \rho \cdot (9{,}52\ C_U + 2{,}56 C_{Th} + 3{,}48 C_K) \times 10^{-5} \quad [1]$$

where ρ is the rock density (kg m^{-3}); C_{U} and C_{Th} are the concentration of uranium and thorium in μ*g g^{-1}*, respectively; and C_{K} is the potassium concentration in %, converted from its oxide form to the elemental form (K_2O) by Eq. 2:

$$c_K = 0.830 \cdot c_{K_2O} \quad [2]$$

The concentrations of uranium, thorium, and potassium were considered to estimate the heat generation rate. Samples from anorthosite and charnockite complex outcrops were prepared for geochemical analysis, in addition to those from anorthosite wells. A minimum of 30 g of each sample was pulverized and sent for chemical analysis made by inductively coupled plasma mass spectrometry (Mnculwane, 2022).

3.2. Permeability and porosity assessment

3.2.1. Unfractured rock samples

Permeability and porosity measurements in laboratory were performed using an AP-608 automated permeameter-porosimeter, which is a system for inferring gas permeability using Darcy's law and the pressure decay method, as well as porosity using Boyle's law (Raymond et al., 2017). Cylindrical core plugs of each rock sample were prepared, and their dimensions (diameter, height, and weight) were registered in the software to obtain density and grain volume, bulk volume, and sample weight. The equipment was configured to perform all measurements with nitrogen gas at a constant confining pressure of 500 psi.

3.2.2. Fractured rock samples

After the initial measurements, artificial fractures were generated in the rock samples (Figure 2) by exerting a controlled compression pressure force on the sample, until a disequilibrium of the supplied load of more than 1kN was observed (Figure 3). The samples were subsequently subject to permeability and porosity measurements using the same methodology, and results, before and after samples being fractured, were compared.

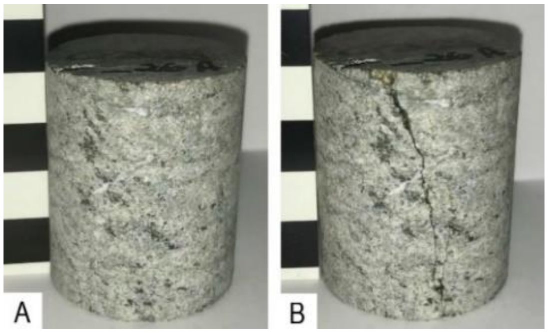

Figure 2. Sample C26 made of metamorphic rock from the Charlevoix charnockite complex. A. Sample before fracturing. B. Sample after fracturing with an applied pressure up to 46.2kN with two new fractures visible at the surface.

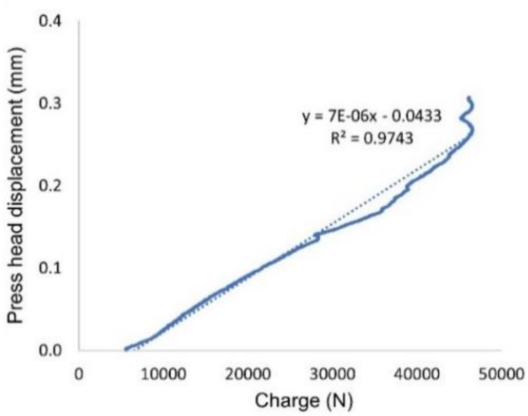

Figure 3. Example of load exerted on rock sample to create artificial fractures.

3.2.3. *In situ* assessment

In the field, permeability of fractured rock was determined by the Porchet method. Water was poured in wells FH-02 and FH-04 to raise the water level. A pressure transducer was used to measure the water level increase and recovery every 10 seconds and to calculate the hydraulic conductivity at the location of each well with Eq.3 (Moreno et al., 2018):

$$K = \frac{r}{2(t_2 - t_1)} ln\left(\frac{h_1 + \frac{r}{2}}{h_2 + \frac{r}{2}}\right) \qquad h_1 > h_2;\ t_1 > t_2 \qquad [3]$$

where h_1 and h_2 [L] are the initial and final water level in the hole, respectively; t_1 and t_2 [T] are the initial and final times, respectively; r is the hole radius [L] and K [LT^{-1}] is the hydraulic conductivity. The *in situ* permeability of the fractured bedrock was calculated by converting hydraulic conductivity to permeability and averaging values obtained for the two tests.

4. RESULTS

4.1. Thermal properties assessment

4.1.1. Thermal conductivity and diffusivity assessment

The thermal conductivity in the Charlevoix crater area has a narrow range of variability among geological formations (Figure 4). The anorthosite outcrop samples show the lowest average thermal conductivity of 1.7 $W\,m^{-1}\,K^{-1}$, while the cores from the boreholes have slightly higher values, around 1.9 $W\,m^{-1}\,K^{-1}$. The charnockite complex has the highest thermal conductivity with an average value of 2.6 $W\,m^{-1}\,K^{-1}$. The thermal diffusivity of the borehole and outcrop samples for the anorthosite and charnockite are within the same range of values.

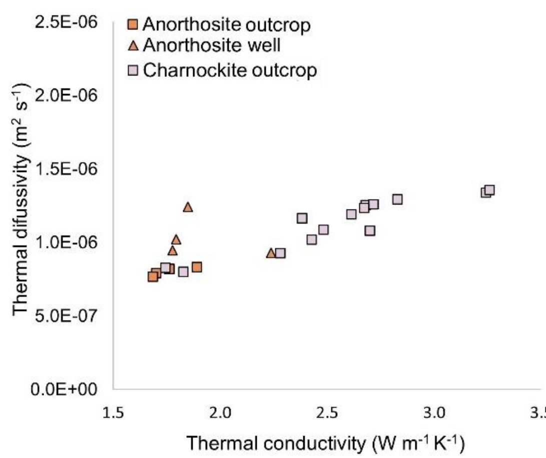

Figure 4. Thermal properties of the rock samples evaluated in the laboratory. Orange markers represent anorthosite and the pink represent charnockite. The triangles represent well samples, and the squares represent outcrop samples.

4.1.2. Internal heat generation

Anorthosite has a lower concentration of uranium and potassium than charnockite (Table 2). The charnockite rocks are the ones with the highest heat generation according to the results.

Table 2. Parameters used to calculate the internal heat generation.

Lithology	Anorthosite		Charnockite
Depth *m*	132-261	Surface	Surface
Density *kg m^{-3}*	2657.0	2661.0	2750.0
232Th *µg g^{-1}*	0.19	0.05	5.12
238U *µg g^{-1}*	0.06	0.01	0.55
K_2O *%*	0.94	0.93	3.74
A ***µW m^{-3}***	0.09	0.08	0.79

4.2. Permeability and porosity assessment

4.2.1. Unfractured rock samples

The permeability and porosity of the laboratory-analyzed samples for both the anorthosite and charnockite rocks are low and similar. They are within the expected theoretical range (Freeze & Cheery, 1979; Figure *5* and Figure *6*). The igneous rocks show an average permeability of 2.2×10^{-13} cm^2 and an average porosity of 1.0 %. Metamorphic rocks have an average permeability of 1.4×10^{-13} cm^2 and an average porosity of 1.7 %.

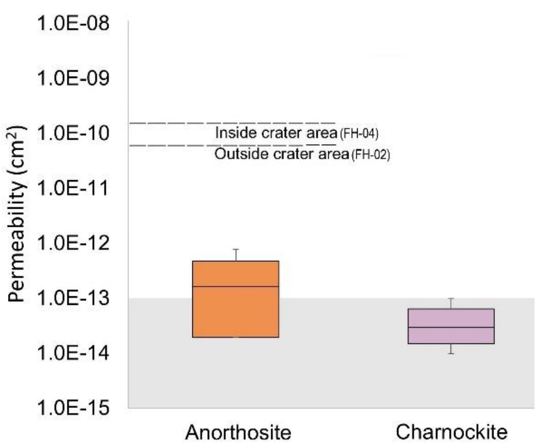

Figure 5. Permeability assessment from outcrops samples. The top box represents quartile one and the bottom box represents quartile three and together enclose 50% of the data. The dividing line of the box represents the median value. The dashed black lines represent the average permeability reported from field tests in boreholes. The gray area represents the general range for unfractured metamorphic and igneous impermeable values according Freeze & Cherry, 1979.

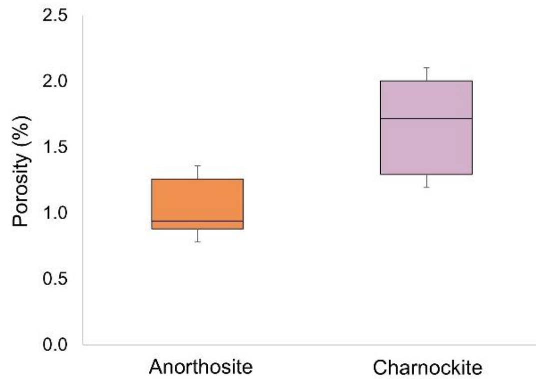

Figure 6. Porosity assessment from outcrop samples. The top box represents quartile one and the bottom box represents quartile three and together enclose 50% of the data.

4.2.2. Fractured rock samples

Permeability increased significantly in all samples after fracturing (Figure 7). Charnockite permeability increased by approximately 3 orders of magnitude, while anorthosite increased by approximately 2 orders of magnitude.
Porosity was less affected by the presence of fractures, remaining close to the same values of the non-fractured rocks, except for C3, where the porosity slightly decreased, which can be due to measurement errors (Figure 8).
It is important to highlight that the samples have different degrees of fracturing, which was difficult to control when imposing the loads and could influence the magnitudes of measured permeability values. In any cases, measurements are characteristics of fractured rocks permeability at a small scale.

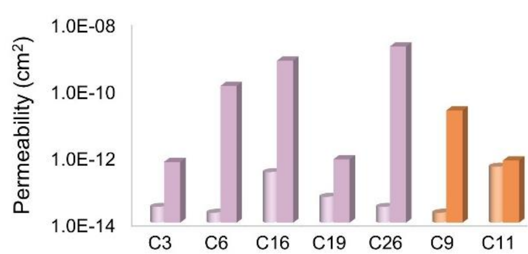

Figure 7. Permeability in rock samples before and after artificial fracturing.

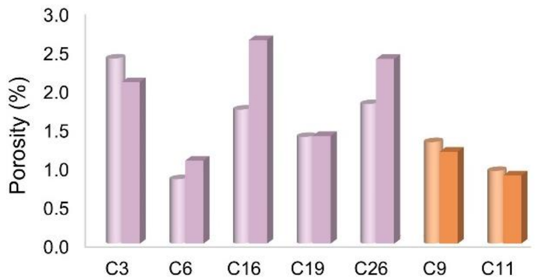

Figure 8. Porosity in rock samples before and after artificial fracturing.

4.2.3. *In situ* assessment

Permeabilities reported from the field test in wells drilled in anorthosite rocks were higher than those evaluated in the laboratory (Figure 5). The one measured in FH-04 well, inside the crater area, shows the highest value of 1.10×10^{-10} cm^2, which falls within the range of fractured igneous rocks (Freeze & Cherry, 1979). The maximum water level for FH-02 was 14.3 m and it decreased to 12.7 m, and for FH-04 it ranged from 15.26 m to 12.28 m. More field tests would be needed to affirm that the permeability in the field is higher but only two wells could be tested due to field constraints.

5. DISCUSSION AND CONCLUSIONS

In this work, thermohydraulic properties of the main geological formations in the Charlevoix crater area were evaluated. The thermal conductivity range for igneous rocks is between 2.0 and 3.0 W m^{-1} K^{-1}, depending on their feldspar content (Clauser, 2011). The thermal conductivity of the carter rocks ranges between 1.7 and 2.6 W m^{-1} K^{-1}, with the anorthosite having the lowest conductivity, thus demonstrating its isolating potential that may provide a thermal blanket effect.

The Earth's interior gains heat in different ways, one of which is through radiogenic heat from the decay of unstable and radioactive isotopes (Clauser, 2011). Guillou and Frottier (1995) reported internal heat generation data in well samples for charnockite in the Les Éboulements sector of 1.6 µW m^{-3}, and for anorthosite in the Clarke City sector of 0.1 µW m^{-3}. The values found for each geological formation (Table *2*) are low, even those taken from samples at depth, so it would not be possible to consider any of these formations as a potential heat source.

The average permeability for both unfractured anorthosite and charnockite rocks are close to each other and are within the theoretical range for igneous and unfractured metamorphic rocks, which is 1×10^{-13} cm^2 to 1×10^{-16} cm^2 (Freeze & Cherry, 1979). The permeability of artificially fractured samples is at least 2 orders of magnitude higher than that of unfractured samples for both rock types (Figure 7) and are within the theoretical range for these fractured rocks. Both anorthosite and charnockite rocks have low porosity (Figure 6). This parameter is mainly controlled by rock type and alteration processes (Rejeki et al 2005), so the presence of fractures does not significantly affect the porosity of each rock, as shown by the results (Figure 8).

Reactivation of faults and the increase of fracture density in the study area was attributed to a meteorite impact event (Rondot, 1968). In geothermal systems, fluid movement occurs through open fractures and the network they provide in the rock mass through intersections. Due to the local geological context, the basement rock is fractured, such that fluid can preferentially flow through the fractures and not through the matrix that was shown to have a low porosity.

A permeability below 1.0×10^{-12} cm^2 and a thermal conductivity between 1.8 and 2.6 W m^{-1} K^{-1} is characteristics of conductive heat transfer and suggest the presence of a petrothermal system. A permeability above 1.0×10^{-11} cm^2 with the same thermal conductivity range begins to allow for conductive-convective heat transfer in transitional systems (Sass & Götz, 012). Permeability assessment of fractured rock samples and in situ measurements resulted in values that are high enough for convection to be considered as a potential heat transfer mechanism in rocks of the Charlevoix crater. Permeability of the fractured rocks evaluated in the laboratory (4.11×10^{-12} cm^2) is still below the permeability found with the field assessments (9.6×10^{-11} cm^2), evidencing the scale effect associated to permeability. This scale effect observed should be considered in addition to the behaviour usually observed in fractured rocks, where the reduction in fracture spacing and aperture with depth generates a decrease in permeability (Singhal and Gupta, 2010). Roughness of the fracture walls can also explain the difference between field and laboratory observations of fractured rock permeability.

The degree of fracturing of each rock sample analyzed in this work was not uniform, even in samples belonging to the same geological formation. X-ray images obtained using a medical CT-scan to analyze the samples before and after fracturing could be made to establish the internal geometry of the fracture network generated and verify the if the permeability of the fractured sample matches that obtained with the cubic law. In addition, structural measurements could be made in outcrops to evaluate permeability from the fracture distribution, and to validate the representativity of the values obtained in the laboratory. This analysis would help to define permeability to be used as input in numerical models to simulate groundwater flow and heat transfer in the Charlevoix carter to infer the subsurface temperature. The next step of this research will be to develop numerical models to evaluate the geothermal potential of the Charlevoix crater.

6. REFERENCES

Abramov, O., & Kring, D. A. (2004). Numerical modeling of an impact-induced hydrothermal system at the Sudbury crater. Journal of Geophysical Research E: Planets, 109(10), 1–16. *https://doi.org/10.1029/2003JE002213*

Allen, D. M., Ghomshei, M. M., Sadler-Brown, T. L., Dakin, A., & Holts, D. (2000). The Current Status of Geothermal Exploration and Development in Canada. World Geothermal Congress, Kyushi-Tohoku, Japan, 55–58.

Bauer, J. F., Krumbholz, M., Meier, S., & Tanner, D. C. (2017). Predictability of properties of a fractured geothermal reservoir: the opportunities and limitations of an outcrop analogue study. Geothermal Energy, 5(1). *https://doi.org/10.1186/s40517-017-0081-0*

Buchbinder, G. G. R., Lambert, A., Kurtz, R. D., Bower, D. R., Anglin, F. M., & Peters, J. (1988). Twelve years of geophysical research in the Charlevoix seismic zone. Tectonophysics, 156(3–4), 193–224. *https://doi.org/10.1016/0040-1951(88)90060-1*

CERM / UQAC. (2015). Résultats du programme d'acquisition de connaissances sur les eaux souterraines des territoires municipalisés de Charlevoix, de Charlevoix-Est et de La Haute-Côte-Nord. Centre d'études sur les ressources minérales, Université du Québec à Chicoutimi, Canada. Report scientifique.

Clauser, C. (2011). Thermal storage and transport properties of rocks, II: Thermal Conductivity and Diffusivity. In Encyclopedia of Solid Earth Geophysics (pp. 1–24). *https://doi.org/10.1007/978-90-481-8702-7*

Freeze, A., Cherry, J. (1979). Groundwater. Prentice-Hall, Inc. *ISBN 0-13-365312-9*

Guillou-Frottier, L., Mareschal, J. C., Jaupart, C., Gariépy, C., Lapointe, R., & Bienfait, G. (1995). Heat flow variations in the Grenville Province, Canada. Earth and Planetary Science Letters, 136(3–4), 447–460. *https://doi.org/10.1016/0012-821X(95)00187-H*

Hecht, J., Fuentemayot, M., Bello, L., & Molina, N. (2012). Uso de la energía geotérmica somera- Un reto alcanzable para los países latinoamericanos. Revista Latinoamericana de Hidrogeología, 8, 48–57. *https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0667.pdf*

Henkel, H., Bäckström, A., Bergman, B., Stephansson, O., & Lindström, M. (2005). Geothermal Energy from Impact Craters? The Björkö Study. World Geothermal Congress, Antalya, Turkey, 24–29.

Lamontagne, M., Keating, P., & Toutin, T. (2000). Complex faulting confounds earthquake research in the charlevoix Seismic Zone, Québec. Eos, 81(26). *https://doi.org/10.1029/00EO00213*

Lemieux, Y. (2001). Analyse structurale des failles supracrustales de la région de Charlevoix, Québec: relations avec l'impact météoritique. Université du Québec, INRS-Géoressources. Mémoire de Matrîse. Québec, QC, Canada.

Lemieux, Y., Tremblay, A., & Lavoie, D. (2003). Structural analysis of supracrustal faults in the Charlevoix area, Quebec: Relation to impact cratering and the St-Laurent fault system. Canadian Journal of Earth Sciences, 40(2), 221–235. *https://doi.org/10.1139/e02-046*

Mareschal, M., & Chouteau, M. (1990). A magnetotelluric investigation of the structutal geology beneath Charlevoix Crater, Quebec. Phys. Earth Planet. Inter., 60: 120—131.

Moreno, D., Lopez-Sanchez, J., Blessent, D., Raymond, J. 2018. Fault characterization and heat-transfer modeling to the Northwest of Nevado del Ruiz Volcano. Journal of South American Earth Sciences, 88, 50–63. *https://doi.org/10.1016/j.jsames.2018.08.008*

Mnculwane, H. T. (2022). Rare Earth Elements Determination by Inductively Coupled Plasma Mass Spectrometry after Alkaline Fusion Preparation. Analytica, 3(1), 135–143. *https://doi.org/10.3390/analytica3010010*

Paulillo, A., Cotton, L., Law, R., Striolo, A., & Lettieri, P. (2020). Geothermal energy in the UK: The life-cycle environmental impacts of electricity production from the United Downs Deep Geothermal Power project. Journal of Cleaner Production, 249, 119410. *https://doi.org/10.1016/j.jclepro.2019.119410*

Popov, Y., Beardsmore, G., Clauser, C., & Roy, S. (2016). ISRM Suggested Methods for Determining Thermal Properties of Rocks from Laboratory Tests at Atmospheric Pressure. Rock Mechanics and Rock Engineering, 49(10), 4179–4207. *https://doi.org/10.1007/s00603-016-1070-5*

Raymond, J., Malo, M., Tanguay, D., Grasby, S., & Bakhteyar, F. (2015). Direct utilization of geothermal energy from coast to coast: a review of current applications and research in Canada. World Geothermal Congress, Melbourne, Australia, 19–25.

Rejeki, S., Hadi, J., & Suhayati, I. (2005). Porosity Study for Detail Reservoir Characterization in Darajat Geothermal Field, West Java, Indonesia. World Geothermal Congress, Antalya, Turkey, 24–29.

Robertson P. B. (1968). La Malbaie Structure, Quebec-A Palaeozoic Meteorite Impact Site. Meteoritics, 4(2), 89–112. *https://doi.org/10.1111/j.1945-*

5100.1968.tb00377.x

Rondot, J. (1968). Nouvel impact météoritique fossile? La structure semi-circulaire de Charlevoix. Canadian Journal of Earth Sciences, 5(5), 1305–1317. *https://doi.org/10.1139/e68-128*

Sass, I., & Götz, A. E. (2012). Geothermal reservoir characterization: A thermofacies concept. Terra Nova, 24(2), 142–147. *https://doi.org/10.1111/j.1365-3121.2011.01048.x*

Vélez, M. I., Taborda, M. A., Miranda, M., Moreno, D., Raymond, J., Lopez, J., Blessent, D., Daniele, L., & Oviedo, M. J. (2020). Preliminary Thermohydraulic characterization of rock samples from two geothermal areas: Charlevoix crater (Canada) and Nevado del Ruiz Volcano (Colombia). World Geothermal Congress, Reykjavik, Iceland, 1–10.