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Preliminary Thermo-Hydraulic Characterization of Rock Samples from Two Geothermal Areas: Charlevoix Crater (Canada) and Nevado del Ruiz Volcano (Colombia)

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ABSTRACT

The Charlevoix region in Quebec Province (Canada) and the Nevado del Ruiz Volcano in Caldas Department (Colombia) are areas of interest for geothermal development where resources are hosted in fractured basement rocks. The Charlevoix region, located northeast of Quebec City, is an area affected by a meteorite impact known as the Charlevoix Astroblème. Inside the crater, high fracture density is expected due to the energy released by the meteorite impact. The presence of insulating rocks such as the Saint-Urbain Anorthosite may favor the increase of the geothermal gradient. The Nevado del Ruiz Volcano is an active andesitic stratovolcano characterized by a hydrothermal system associated with several hot springs. Volcanism in the area is caused by the subduction of the Nazca Plate below the South American continent.

Thermal properties and permeability were evaluated in the laboratory with samples from both areas during the project with the objective of improving our understanding of the heat transfer mechanisms taking place in fractured basement rocks at both systems. The anorthosite unit in Charlevoix is the formation with lowest thermal conductivity (1.7 W m^{-1} K^{-1}), which confirms that its insulation potential can increase the geothermal gradient. At the Nevado del Ruiz Volcano, the Cajamarca Complex hosting geothermal resources has the highest thermal conductivity (3.5 W m^{-1} K^{-1}). The matrix permeability measured on samples with an air permeameter in the laboratory is 2.80×10^{-12} and 1.93×10^{-11} cm^2 in Charlevoix and Nevado del Ruiz Volcano respectively, which are low values for fractures and igneous and metamorphic rocks. However, because of the fractures observed at outcrops, higher permeability due to secondary porosity is expected to allow groundwater flow and advective heat transfer.

1. INTRODUCTION

Deep geothermal resources are one of the renewable energy alternatives considered to be a viable option to reduce greenhouse gas emissions and mitigate climate change (IPCC et al., 2011). However, the design and exploitation of geothermal reservoirs, especially those hosted in basement rocks lacking of primary porosity, remain challenging. Geological exploration methods to assess heat transfer mechanisms of deep resources from surface measurements in the early exploration phase can thus be improved to facilitate development and unlock deep geothermal resources of fractured basement rocks, such as those associated with the Charlevoix meteorite crater in the province of Quebec and at the Nevado del Ruíz Volcano (NRV) in Colombia.

The Charlevoix region is affected by a meteorite impact known as the Charlevoix Astroblème (CA) with an estimated age of 34 ± 15 Ma (Rondot, 2007). The impact of the meteorite created an intensely fractured area inside the crater that could facilitate groundwater flow. In addition, the presence of insulating rocks in the meteorite impact zones, such as Saint-Urbain anorthosite, could contribute to the increase of the geothermal gradient in this region, allowing higher temperatures at depth when compared to surrounding zones. These two factors are necessary conditions for the exploitation of deep geothermal resources.

Volcanic regions, such as NRV in Colombia, have been the target for the exploitation of geothermal resources. The NRV area is characterized by a hydrothermal system with several thermal springs at surface, making it one of the most studied areas for the development of geothermal resources in Colombia (Alfaro, 2015). High temperatures of 150 and 250 °C are estimated at a depth of 3 km in rocks of the Cajamarca metamorphic complex forming the basement at the roots of the volcanic system (Almaguer, 2013; Ceballos, 2017; Vélez et al., 2018).

The objective of this study is to evaluate the possible heat transfer mechanisms taking place in the fractured rock masses based on: 1) an evaluation of thermal and hydraulic properties made on samples and, 2) fracture network characterization (Sanderson & Nixon, 2015; Miranda et al., 2018). This assessment is conducted in the context of unconventional geothermal resources hosted in basement rocks of Charlevoix crater and Nevado del Ruiz Volcano. In both regions, geothermal resources are hosted in fractured basement rocks where groundwater flow is controlled by secondary permeability. However, the origin of fracturing and geothermal gradients are different at both sites. The NRV is characterized by a geodynamic environment dominated by active tectonism controlling the volcanism and the presence of regional faults and fracture networks (Mejía, 2012; Moreno et al., 2018). At CA, the meteorite impact affecting the region reactivated regional faults (St. Lawrence fault) and created intense fracturing (Lemieux, 2001). The methodology developed during this project can be used in pre-feasibility studies for the assessment of geothermal resources in other regions with fractured basement rocks.

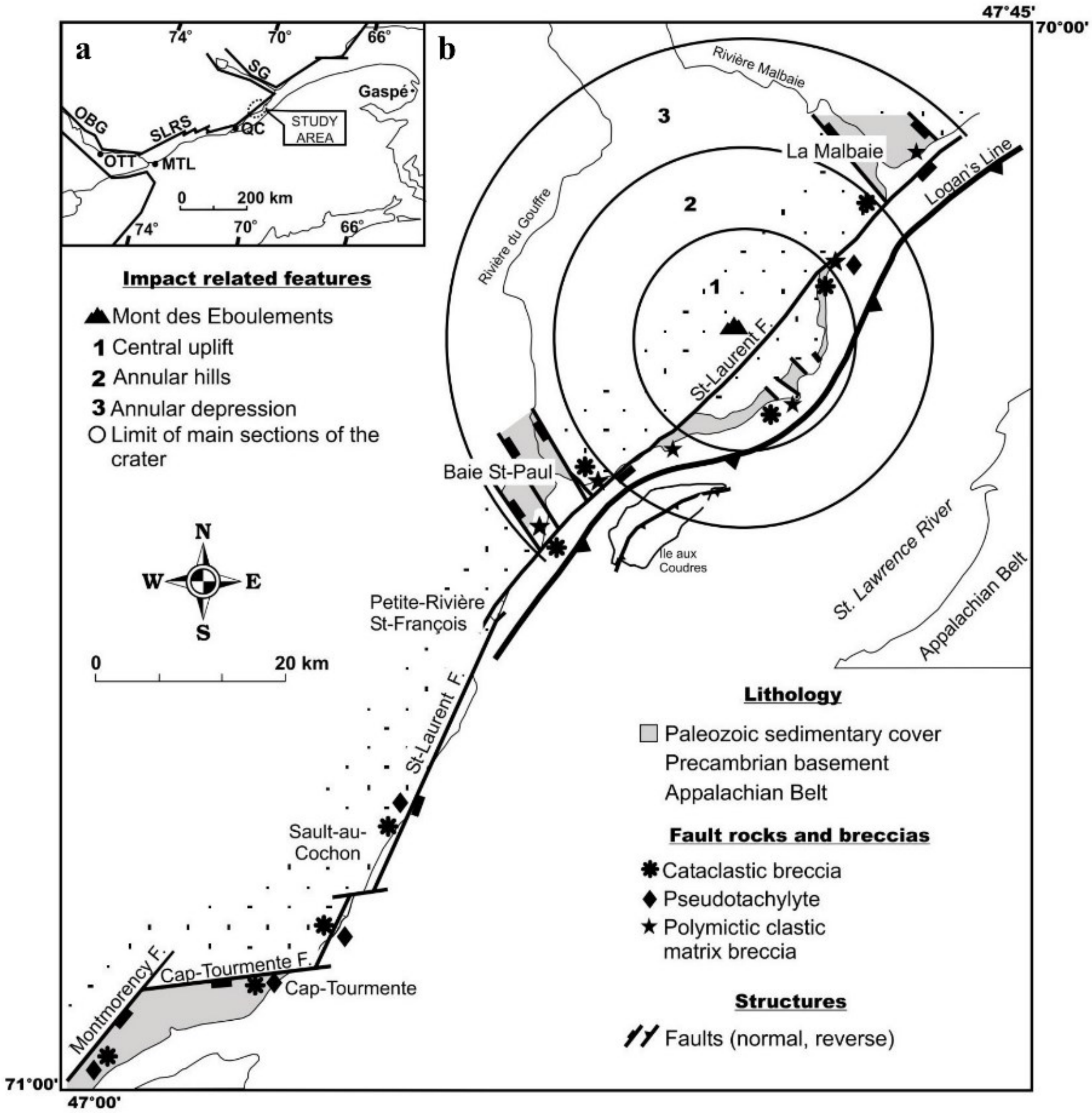

Figure 1. a) Location of the study area and b) Model of the structure of the Charlevoix crater with three annular zones (from Lemieux et al., 2003).

2. REGIONAL CONTEXT

2.1 Charlevoix

The meteorite impact structure of the CA was discovered by Rondot (1968) due to the presence of shatter cones and the geomorphology of the region. The Charlevoix crater is characterized by a semi-circular plain (Figure 1) with an average altitude of 365 m. The Mont des Éboulements with an altitude of 768 m is the geometric center of the structure. The southern half of the crater structure is located under the St. Lawrence River (Rondot, 1968). The diameter of the crater is 56 km and it intercepts three geological provinces: the Grenville Province, the Appalachian Province, and the St. Lawrence Platform. Rock displacement caused by the meteorite impact has been subdivided into 3 major circular zones: 1) Central uplift, 2) Annular hills, and 3) Annular depression (Figure 1; Lemieux et al., 2003).

Inside the crater, a high fracture density due to the energy released by the meteorite impact is observed (Rondot, 1979; Lemieux, 2001). The Charlevoix region includes several fault systems, most of which are NW-SE and NE-SW oriented and are characterized by textures typical of deformation conditions (Lemieux, 2001). Circular faults in the inner domain of the study area and within the limits of morphological features, such as annular depression and central uplift, are attributed to the meteoric impact (Lemieux, 2001). This means that the resulting fracture network could promote groundwater flow. Insulating rocks in meteorite impact craters are known to favor the increase of the geothermal gradient (Henkel et al., 2005). In our case, it is the Saint-Urbain anorthosite that has a low thermal conductivity of approximately 1.8 W m-1 K-1 (Mukherjee & Das, 2002). A temperature of nearly 55 °C is expected at a depth of less than 2 km in the Saint-Urbain anorthosite, which would be adequate for heat production.

Basement rocks in the Grenville Province constitute 95% of the region (Robertson, 1968); this includes the granitic, migmatite and charnockitic gneiss of the Charlevoix Charnockitic Complex and the anorthosite mass of Saint-Urbain intercepting the eastern boundary of the crater (Figure 2). The remaining 5% corresponds to sedimentary units of the St. Lawrence Platform with a succession of siliciclastic and calcareous sedimentary rocks that are commonly less than 80 m thick (Lemieux, 2001).

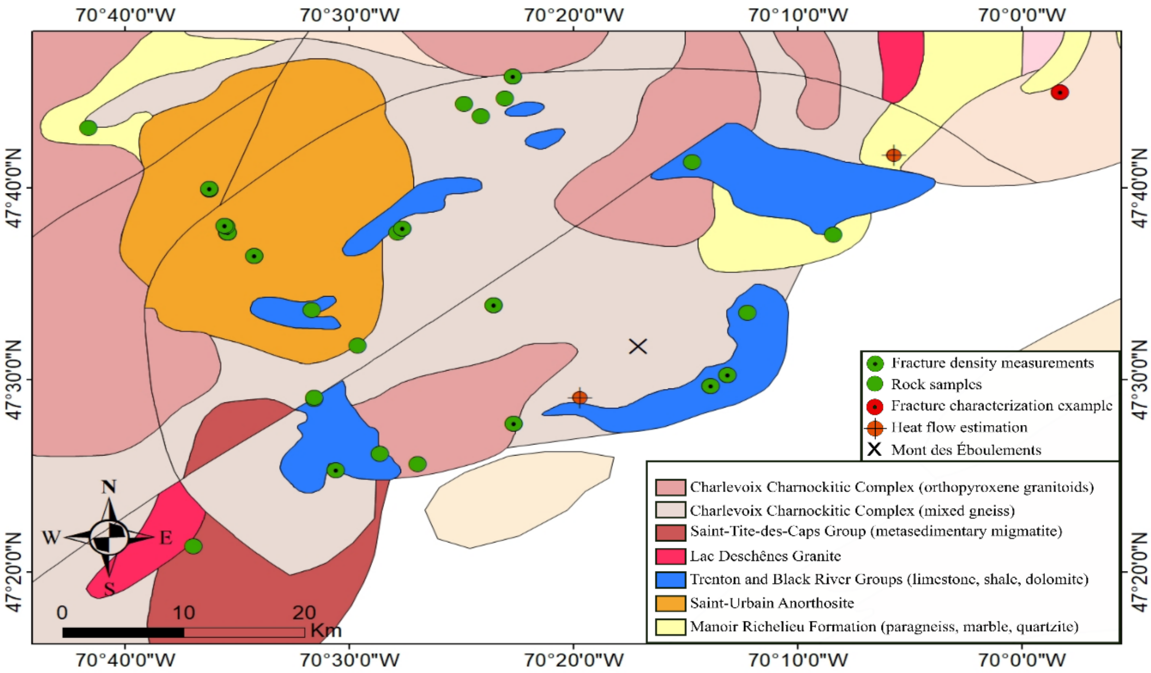

Figure 2. Geological context of the Charlevoix region indicating locations of rock samples collected and fracture density measurements.

2.2 Nevado del Ruiz Volcano

The Nevado de Ruiz volcano (NRV) is an active stratovolcano, located in Los Nevados National Natural Park (PNN), in the middle of the central Colombian mountain range (Figure 3). Volcanic activity in this region is due to the subduction of the Nazca plate below the South American plate. The region is dominated by the presence of metamorphic and igneous units with different degrees of deformation (Mejía, 2012). The Cajamarca complex consists of all the metamorphic basement rocks of the central cordillera; its composition is heterogeneous and results from several regional metamorphic episodes, overlaid by local thermal or dynamic effects of varying intensity (Figure 4; González, 2001). The Quebrada Grande complex consists of a group of sedimentary and volcanic rocks that form a large part of the western flank of the Central Cordillera. This complex is characterized by interactions of volcanic with sedimentary rocks of large lithological variations, both in the sedimentary sequence and in the relationship between volcanic fluids and pyroclastic layers (González, 2001). Andesite lava flows constitute a thick layer of extrusive rocks lying on the igneous and metaphorical rocks of the Central Cordillera (Figure 4).

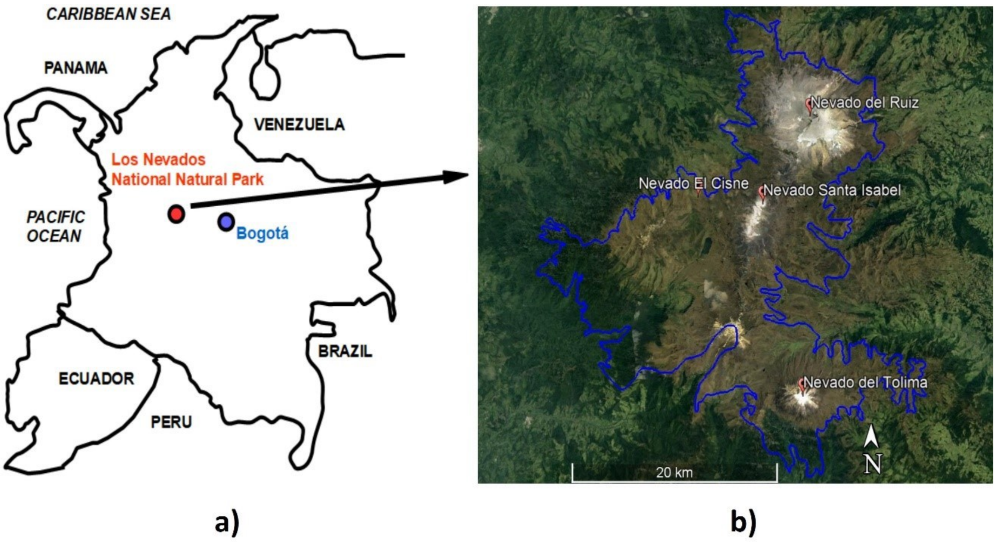

Figure 3. a) Location of Parque Nacional los Nevados in Colombia and b) Location of Nevado del Ruiz (modified from Vélez et al., 2018).

The first pre-feasibility study in the region was carried out in the late 1960s by the Italian company ENEL (Ente Nazionale per the Energia Elettrica) in collaboration with CHEC (Central Hidroeléctrica de Caldas) and described the lithostratigraphic, volcanological, structural and hydrogeological characteristics of the NRV complex (Arango et al., 1970). In 1977, a 1466 m deep exploration well (Las Nereidas) was drilled on the west side of the volcano. In this borehole, seven lithological units with hydrothermal alteration were identified and a temperature of about 200 °C was measured at the bottom of the borehole (Monsalve et al., 1998). Recent studies were conducted between 2011 and 2013 with the support of the company ISAGEN, which drilled two 300 m deep exploration wells on the western flank of the NRV volcano (Rojas, 2012). That was when temperature profiles and electrical resistivity tests were made.

A first estimate of the temperature at reservoir scale was presented by Vélez et al. (2018) based on laboratory thermal conductivity measurements of rock samples collected at outcrop and numerical modeling. A temperature between 150 and 250 °C is expected at a depth of 3 km in an area outside the national natural park Los Nevados (Figure 4). A heat transfer model along fault zones was presented by Moreno et al. (2018), which indicates the influence of fault direction and dip in response to the regional hydraulic gradient, and consequently in the heat transfer mechanisms that define the geothermal potential of the area.

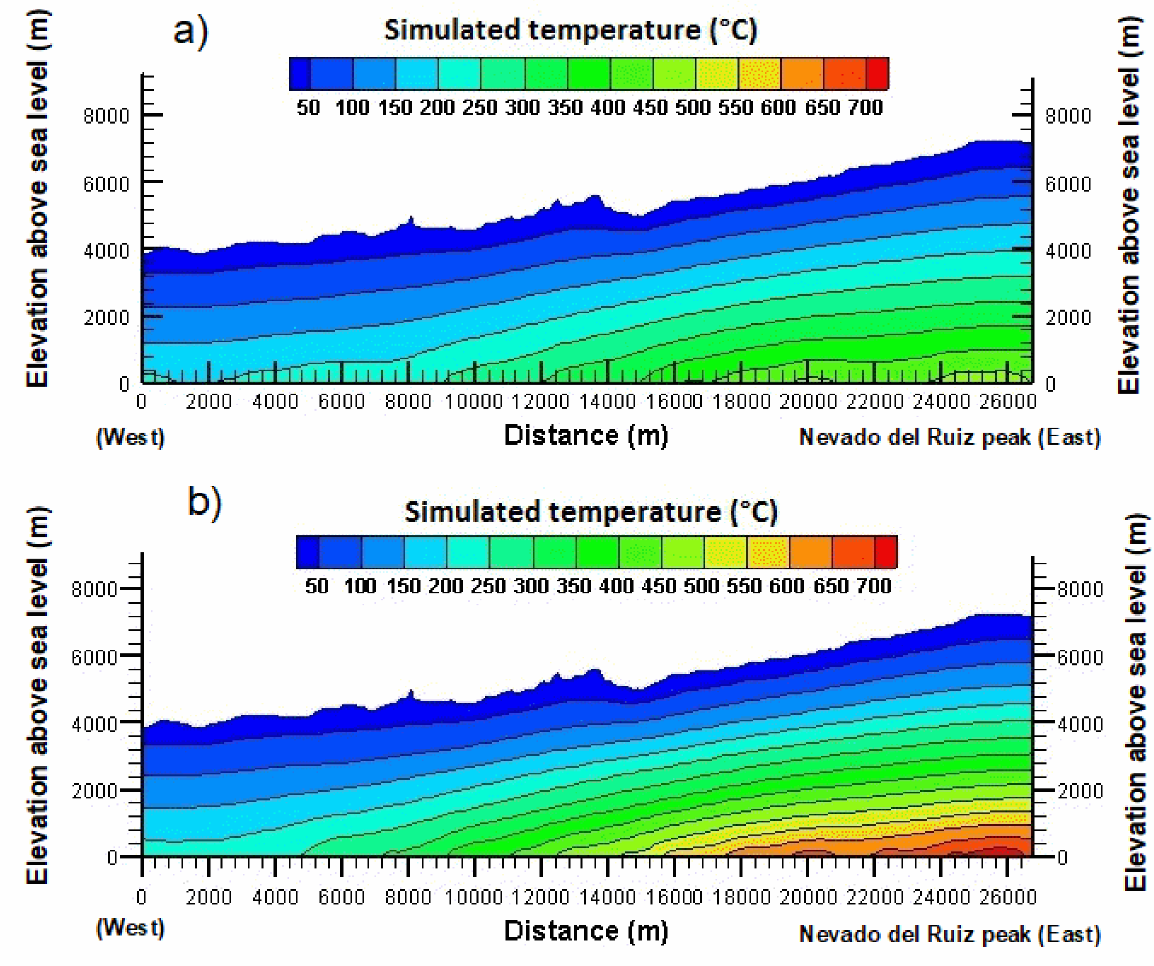

Figure 4. Simulated temperature distribution for a) constant thermal conductivity and b) temperature dependent thermal conductivity (Vélez et al., 2018).

3. FIELD WORK

During the initial phase of the project, rock samples from the different geological units outcropping in both areas of interest (CA and NRV) were collected and used for laboratory analysis. The field campaign in NRV occurred between 2014 – 2018 in collaboration with the Universidad de Medellín in Colombia providing additional data to the project. Surface structural surveys to characterize fracture networks have been conducted in the Charlevoix region in September 2018 (Figure 5) and at the NRV in July 2019. However, data collected at NRV have not been processed yet. The orientation, spacing and aperture of fractures, as well as the relationships between the characteristic elements of the fracture network (branches and nodes) were inventoried. A distinction between the fracturing related to the meteorite impact and the tectonic processes was not made in this study. The research published by Lemieux et al., (2003) and Lemieux (2001) suggests that faulting in the Charlevoix region occurred both before and after the meteoric impact making difficult to distinguish the fracturing origins. This characterization was used to classify and count different types of nodes (Sanderson & Nixon, 2015) formed between fractures and to estimate the effective permeability of the fractured rock according to the methodology proposed by Saevik & Nixon (2017).

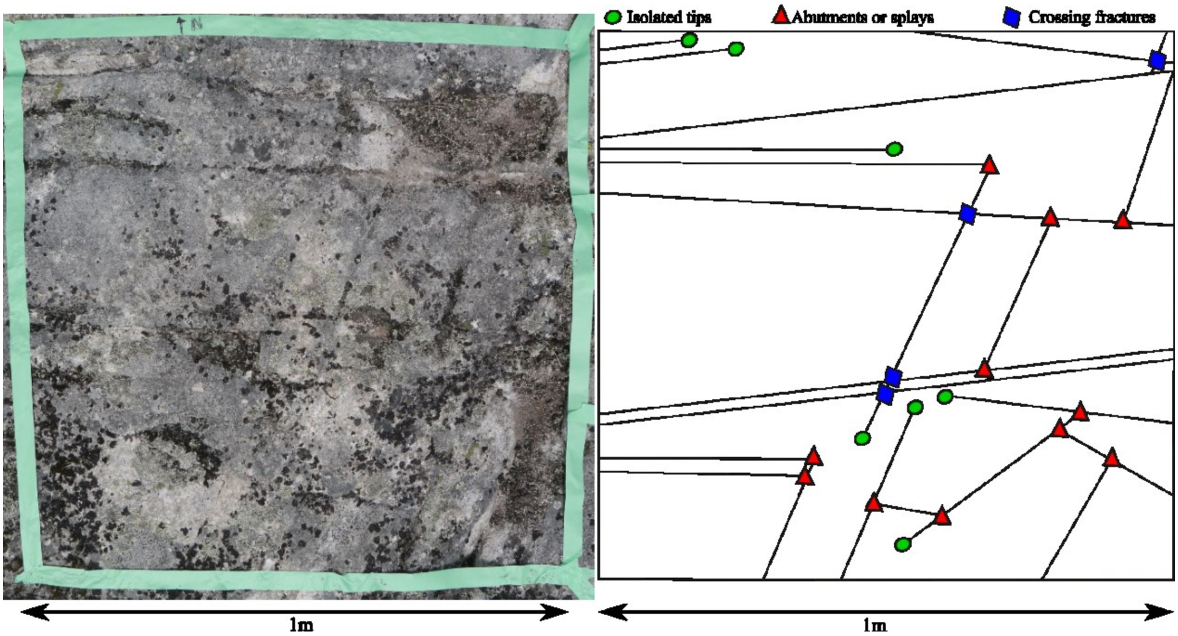

Figure 5. Example of fracture network characterization carried out at a migmatite outcrop in Charlevoix (location indicated in Figure 2).

4. LABORATORY ANALYSIS AND FRACTURE NETWORK CHARACTERIZATION

The thermal conductivity and thermal diffusivity of rock samples were measured with an infrared or thermal conductivity scanner (Popov et al., 2017). This instrument was made by LGM Lippmann and allows thermal conductivity and thermal diffusivity to be measured transiently at room temperature. The instrument is based on the optical scanner method developed by Popov et al. (1999). A moving optical head with an infrared heat source and temperature sensors measures the temperature variation along the sample. Temperature sensors are located before and after the heat source to measure the undisturbed and disturbed temperature. Thermal properties are inferred by comparing the temperature variation of the rock sample with the temperature variation of the reference samples placed before and after the rock sample. The evaluation range for thermal conductivity and diffusivity is 0.2 to 25 W m^{-1} K^{-1} and 0.6×10^{-6} to 3.0×10^{-6} m^2 s^{-1}, with an accuracy of 3 and 5%, respectively. Cumulating local measurements of thermal conductivity along the surface of the samples allowed assessing the heterogeneity of the rock.

Based on the thermal conductivity and diffusivity analyses, the volumetric heat capacity of the samples was calculated as (Eq. 1):

$$\rho c = \frac{\lambda}{\alpha} \quad (1)$$

where ρ (kg m^{-3}) is the density, c (kJ kg^{-1} K^{-1}) is the specific heat capacity, λ (W m^{-1} K^{-1}) is the thermal conductivity and α (m^2 s^{-1}) the thermal diffusivity. The permeability of rock samples were measured with a portable gas permeameter (PPP 250; Core Lab, 2016). The permeameter is used to measure the permeability of the rock matrix on outcrops or rock samples. The analysis of the permeability is based on the transient pressure drop method (American Petroleum Institute, 1998). The pressure of the gas entering the rock is measured to deduce the permeability using Darcy's law in a range between 9.87×10^{-12} and 4.93×10^{-8} cm^2 (Filomena et al., 2014).

The node counting method described by Sanderson & Nixon (2015) and Saevik & Nixon (2017) is based on the characterization of the fracture network on the outcrop surface. The method was used to assess the fracture density and connectivity between fractures. The number of branches (N_b, Eq. 2) and the average number of connections per branches (C_b, Eq. 3) were estimated for each location where fractures were recorded:

$$N_b = \frac{1}{2}\left(N_i + N_y + N_x\right) \quad (2)$$

$$C_b = \frac{3N_y + 4N_x}{N_b} \quad (3)$$

The mechanical aperture (a_m) of the fractures measured at surface is transformed into hydraulic aperture (a_h) with Equation 4 (Lee et al., 1995; Barton & de Quadros, 1997) as:

$$a_h = \frac{a_m^2}{JRC^{2.5}} \quad (4)$$

where JRC is the fracture roughness coefficient, which varies within the range of 20 (rough surface) to 0 (smooth surface). In very irregular natural fractures, the JRC can vary from 3 to 12 from one part of the fracture to another (Singhal & Gupta, 2010). The hydraulic aperture of the fractures is then used to estimate their hydraulic conductivity K_f (m s^{-1}) considering the parallel plate model (Eq. 5):

$$K_f = \frac{\gamma (a_h)^2}{12\mu} \tag{5}$$

where γ ($N\ m^{-3}$) and μ (Pa s) are the specific weight and the dynamic viscosity of water, respectively, at the temperature of interest.

5. RESULTS

The thermal conductivity of the rock samples in the Charlevoix region varies between 1.74 to 3.27 W $m^{-1}\ K^{-1}$ and the anorthosite formation (igneous) has the lowest thermal conductivity with a mean value of 1.87 W $m^{-1}\ K^{-1}$ (Figure 6a). At the NRV, the thermal conductivity has a great variability ranging between 0.44 to 5.62 W $m^{-1}\ K^{-1}$, with the highest values in the Cajamarca complex (metamorphic rocks) and the lowest value represented by the andesite (extrusive igneous; Figure 6b). A decrease in thermal conductivity with the increment in rock porosity is observed for the andesite samples similarly to that observed for volcanic rocks reported by Clauser (2006). The heat capacity of the rocks present in Charlevoix varies between 2025 and 2898 J $m^{-3}\ K^{-3}$, while at the NRV region, it ranges between 1440 and 3686 J $m^{-3}\ K^{-3}$.

The matrix permeability of the rock samples in both areas is low, ranging between 5.87×10^{-12} to 1.66×10^{-11} cm^2 in Charlevoix (Figure 7a) and from 4.72×10^{-12} to 1.95×10^{-10} cm^2 in NRV (Figure 7b). These values correspond to the lowest permeability range observed in fractured igneous and metamorphic rocks (Freeze & Cherry, 1979). However, it is expected to find higher secondary permeability in the areas.

Field fracture network characterization allows assessing the connectivity between the fractures in each sampling area. The average number of connections per branch (C_b) varies between zero and two. A value of 2 indicates doubly connected branches, 1 partially connected branches, and 0 isolated branches (Sanderson & Nixon, 2015). The average C_b is 1.86 for the 15 sampling areas of CA, indicating that the branches are mainly double connected (Figure 8). The number of nodes, normalized to 1 m^2 area, varies between 13 and 273 (Figure 8). The maximum value was observed in an area with the presence of shatter cones, one of the features of meteorite impacts that is characterized by fractures in a conical shape (Robertson, 1968; Rondot, 1979).

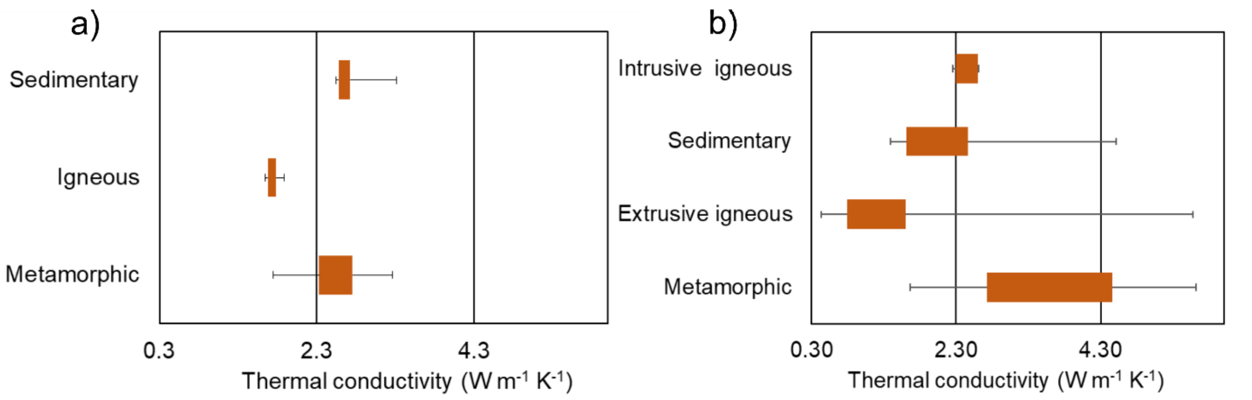

Figure 6. Thermal conductivity of the rock types analyzed in a) Charlevoix region and b) NRV region.

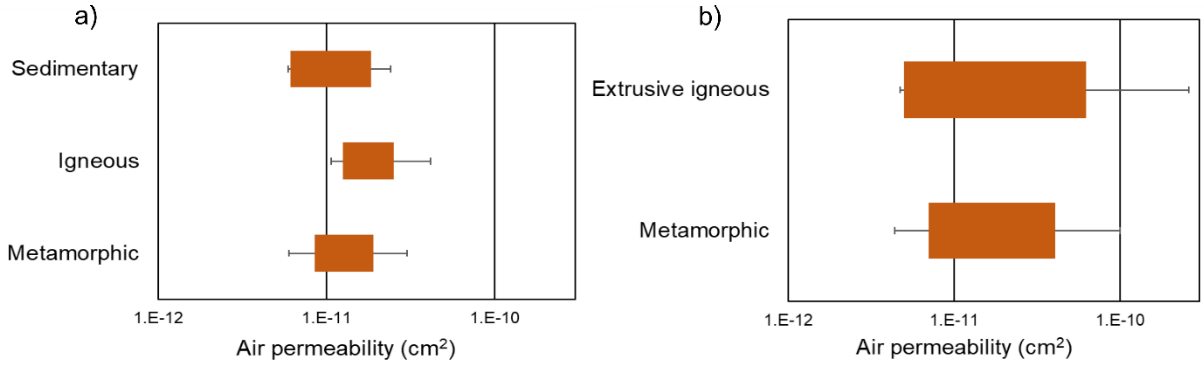

Figure 7. Permeability of the rock matrices analyzed in a) Charlevoix region and b) NRV region.

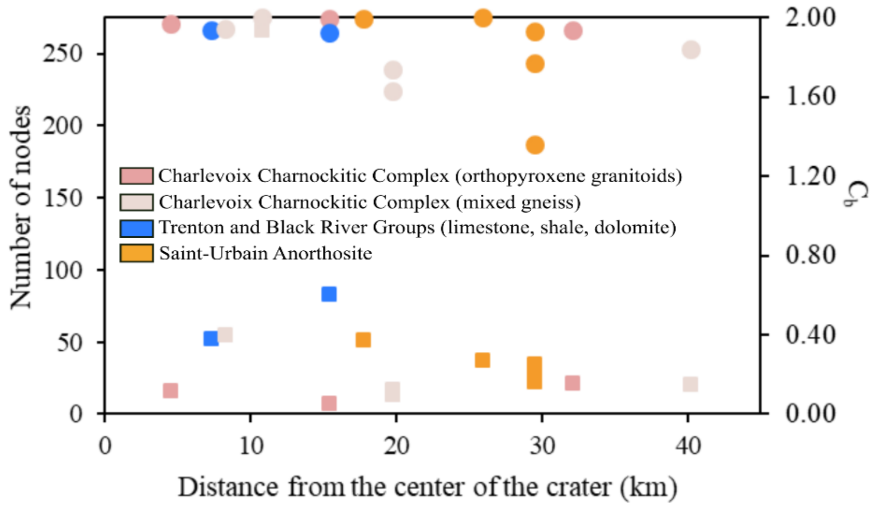

Figure 8. Number of nodes (squares) and average number of connections per branches (C_b, circles) at the fracture sampling sites of the Charlevoix region.

The hydraulic conductivity of the fractures was estimated from Equations 4 and 5 using the mechanical aperture of the fractures measured at outcrops, whose average value was 2.06 mm and a JRC value of 3, corresponding to the minimum value for natural fractures (Singhal et al., 2010); the water specific weight and viscosity were set to 9781 N m^{-3} and 0.0011 Pa s^{-1} respectively. The resulting average hydraulic aperture is thus 0.42 mm, while the permeability ranges between 3.61×10^{-4} cm^2 in the sedimentary rocks of the Trenton and Black River groups and 2.33×10^{-3} cm^2 for the anorthosites which are higher values compared to the matrix permeability. However, these values are not representative of the condition at higher depth because the outcrops are exposed to weathering conditions altering the physical properties of the exposed rocks. However, it is an initial approximation to the hydraulic properties of the formation in the region. Predicting reservoir properties from outcrops studies can be challenging as discussed by Bauer et al., (2017). An evaluation of the rocks samples permeability and fractures permeability will be carried out in the next step of the project.

The geothermal gradient in the Charlevoix region has been estimated from two heat flow evaluations with equilibrium temperature measurements (Mareschal et al., 2000; Mareschal & Jaupart, 2004) and from thermal conductivity measured in the lab, but measurements were achieved outside the anorthosite complex of interest for this study. The geothermal gradient was thus estimated in the Saint-Urbain Anorthosite and in the gneiss from the Charlevoix Charnockitic complex (Figure 9) based on thermal conductivity evaluation from this study and the previous knowledge of heat flow. In the anorthosite rock mass, the geothermal gradient estimated taking into account the paleoclimate perturbation (Bédard et al., 2017; Jessop, 1990) is 31.6 °C km^{-1}, which is higher than the value of 18.5 °C km^{-1} estimated in the remaining portion of the crater.

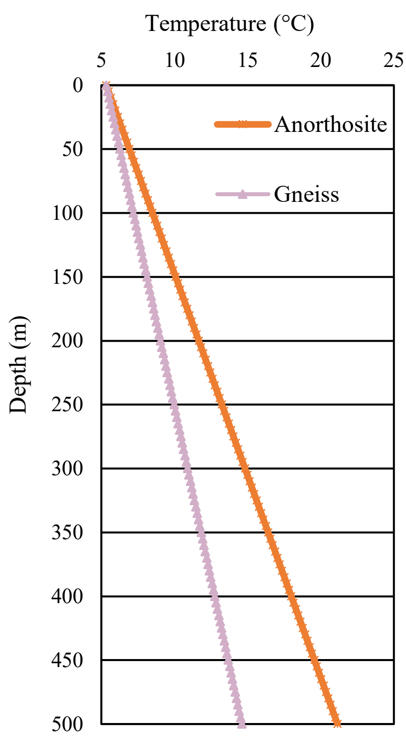

Figure 9. Geothermal gradient estimated in Charlevoix region.

6. DISCUSSION AND CONCLUSIONS

The thermal conductivity of the igneous rocks corresponding to the anorthosite formation has the lowest value in the Charlevoix region, providing a potential to increase the geothermal gradient by a factor of 1.7 when compared to the surrounding rocks. The potentially higher geothermal gradient in the Saint-Urbain area makes this region favorable to the development of geothermal resources for space heating. In the NRV region, the lithology with the lowest thermal conductivity is the extrusive igneous rocks, mainly represented by andesites and ignimbrites. These formations are approximately 500 m thick (CHEC, 1983) and lie above the Cajamarca Complex (metamorphic unit) acting as an insulating layer to heat transfer (Vélez et al., 2018) and allowing to find higher temperatures in the basement rocks of the Cajamarca Complex. This last formation has the highest thermal conductivity and can host a potential reservoir in its basement (Almaguer, 2013; Vélez et al., 2018).

The fracture network characterization indicates a high connectivity between the fractures in CA with a 63.7% of double connected fractures, 27.6% of partially connected fractures and 8.7% of isolated tips. A correlation between the number of fractures and the distance from the center of the crater was not observed. The highest number of fractures was found in the sedimentary rocks from the Trenton and Black River groups and in an area with shatter cones in the Charlevoix Charnockitic complex.

The matrix permeability measured in both areas is low. The portable probe permeameter (Core Lab, 2016) provides an initial approximation to the permeability of the rock samples collected in the field. This instrument measures the air permeability of the porous matrix, which can be higher than the absolute liquid permeability of the sample due to the tendency of gas molecules to slip on the surface of the porous media (Tanikawa & Shimamoto, 2009; Al-Jabri et al., 2015). This phenomenon is known as the Klinkenberg effect and when the permeability is measured at several pressures, a correction can be applied. In this study, permeability was measured only at atmospheric pressure; therefore, the results are presented in the form of air permeability such that higher water permeability is expected. Moreover, both regions are characterized by the presence of faults and fractures controlling the secondary permeability and allowing advective heat transfer. Considering only the primary permeability may lead to an underestimation of the groundwater flow potential in both target areas. The secondary permeability will be measured at different pressures with a gas permeameter (Coretest Systems, 2017) creating artificial fractures in core samples, as described by Kushnir et al. (2018).

The thermal and hydraulic properties estimated will be used to create a thermo-stratigraphic scale of the two regions of interest as proposed by Sass & Götz (2012). This scale will allow classifying the geological formations according to the expected heat transfer mechanism. In rock formations with low matrix permeability such as those studied, it is expected to find conductive heat transfer as the dominating heat transfer mechanism. Advection becomes the predominant heat transfer mechanism when the permeability exceeds a value of 1×10^{-9} cm^2. The mean matrix permeability was found to be 2.80×10^{-12} and 1.93×10^{-11} cm^2 for CA and NRV, respectively. These values are low when compared to various fractured igneous and metamorphic rocks (Freeze & Cherry, 1979) which means it leads to mainly conductive heat transfer (Sass & Götz, 2012). However, secondary permeability is expected to be higher in both areas of interest and can potentially allow advective heat transfer. This shows the importance of secondary permeability, for which additional work is expected to quantify it, when defining heat transfer mechanism occurring at depth. The thermal and hydraulic properties presented in this study, as well as fracture outcrops characterization, will be used to develop numerical models of heat transfer and groundwater flow and simulate production wells in order to anticipate potential geothermal resource exploitation.

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