EFFECT OF TEMPERATURE-DEPENDENT THERMAL CONDUCTIVITY ON THE TEMPERATURE FIELD AT DEPTH: CASE STUDY OF KUUJJUAQ, CANADA

Mafalda M. Miranda[1,2], Maria Isabel Vélez[1], Jasmin Raymond[1,2]

[1.] INRS – Institut national de la recherche scientifique, Centre Eau Terre Environnement, Québec City, Canada
[2.] CEN – Centre d'études nordiques, Université Laval, Québec City, Canada
mafalda_alexandra.miranda@ete.inrs.ca

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Abstract

This work aims at assessing the influence of temperature-dependent thermal conductivity on the temperature distribution at depth. Thermal conductivity was evaluated at temperatures ranging from 20 to 160 °C. The experimental results were implemented in COMSOL Multiphysics to simulate the temperature at depth. The data was implemented as analytical and interpolation functions. The results reveal that the analytical functions lead to a 11 % increase of the temperature at 5 km. In turn, COMSOL's interpolation function shows an increase of about 9.5 %. This new evaluation predicts temperatures of 105 to 113 ºC at 5 km below Kuujjuaq (Canada).

1. Introduction

Thermal conductivity is temperature-dependent, decreasing with the increase of the later (e.g., Clauser and Huenges et al. 1995). Several empirical relationships have been proposed in the literature to describe this behavior (e.g., Lee and Deming 1998). In this work, thermal conductivity was evaluated at temperatures of 20 to 160 ºC and the results fit to literature functions using the obtained experimental coefficients. The empirical equations were implemented in a finite element model as analytical functions to infer the temperature at depth with heat conduction simulations. The results obtained from the laboratory were additionally implemented as interpolation function. This allowed to quantify the influence of the different functions on the numerical simulation of the temperature at depth.

2. Methods

A total of 9 samples were used to evaluate thermal conductivity at temperatures ranging from 20 to 160 ºC. The dataset comprises 4 paragneiss samples and 5 diorite samples, the main lithologies outcropping nearby Kuujjuaq's community (QC, Canada; **Fig. 1**).

The instrument used to evaluate thermal conductivity is the FOX50 Heat Flow Meter (Raymond et al. 2017). The analysis is made when temperature across the sample reaches steady state. A temperature difference is imposed on both plates and successive data acquisition cycles are run until the temperature of the upper and lower plates and transducer signals satisfy the equilibrium criteria to declare the sample in thermal equilibrium. Then, thermal conductivity is evaluated. Each plate must meet each equilibrium criterion independently. These criteria are: 1) temperature equilibrium (TE) criterion, 2) semi-equilibrium (SE) criterion, 3) percent equilibrium (PE) criterion, 4) number of blocks of PE, and 5) inflexion criterion. The accuracy of the thermal conductivity evaluation with this instrument is about 3 %.

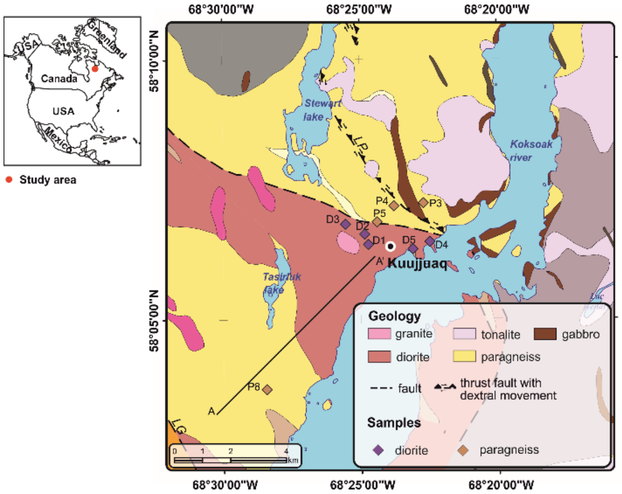

Fig. 1 Geographical and geological setting (adapted from SIGÉOM 2019)

The results were fit to the following relationships:

$$\frac{1}{\lambda(T)} = \frac{1}{\lambda_{20}} + aT \tag{1}$$

$$\lambda(T) = \frac{\lambda_{20}}{1 + b(T - 20)} \tag{2}$$

where λ (W m^{-1} K^{-1}) is thermal conductivity, T (ºC) stands for temperature and a and b are experimental coefficients controling the temperature dependence of the thermal conductivity.

The 2D steady state temperature field at depth was simulated numerically using COMSOL Multiphysics with a finite element approach to solve heat conduction in the crust. The temperature distribution was modeled for a rectangular geometry with a width of 8 km and a depth of 10 km. The center of the 2D model corresponds to a change in lithology between paragneiss and diorite (**Fig. 1**). A constant surface temperature of -1 °C and a constant heat flux of 35.5 mW m^{-2} were set as upper and lower boundary conditions. Further details on the modeling approach are given in Miranda et al. (unpublished). The temperature dependence of thermal conductivity was implemented in the materials as both analytical and interpolation functions. The internal heat generation from radioactive element decay was assumed constant and dependent of the material.

3. Results and discussion

Thermal conductivity as a function of temperature reveals a decrease of more than 40 % (**Table 1**).

Table 1 Thermal conductivity as a function of temperature

T (°C)	λ (W m^{-1} K^{-1})	
	Paragneiss (n = 4)	Diorite (n = 5)
20	2.32	2.39
40	2.28	2.33
60	2.22	2.25
80	2.11	2.10
100	2.05	1.96
120	1.95	1.86
140	1.88	1.78
160	1.63	1.49
Variation ratio	-42 %	-60 %

n – number of samples

Using a constant thermal conductivity, independent of temperature, to simulate the temperature field at depth, a value of about 90 °C is obtained at 5 km depth (**Fig. 2a**). However, if Eq. (1) and (2) are implemented in COMSOL, the temperature at 5 km increases to 113 °C and 107 °C, respectively (**Fig. 2b, c**). Using COMSOL's interpolation function leads to a temperature of 105 °C at 5 km depth (**Fig. 2d**).

Temperature-dependent thermal conductivity leads to an increase on the temperature field at depth. An observation that agrees with the works of Lemenager et al. (2018) and Vélez et al. (2018). The difference between the non-temperature-dependent and temperature-dependent thermal model is up to 12 %. Applying COMSOL's interpolation function, the difference between both models is 9.5 %. A difference of 12 and 10 % is found by implementing Eqs. (1) and (2) as analytical functions.

There is still a high uncertainty due to the lack of deep temperature measurements in Kuujjuak. Nevertheless, this new evaluation of the temperature field below Kuujjuaq indicates potential use of the geothermal resources for direct space heating.

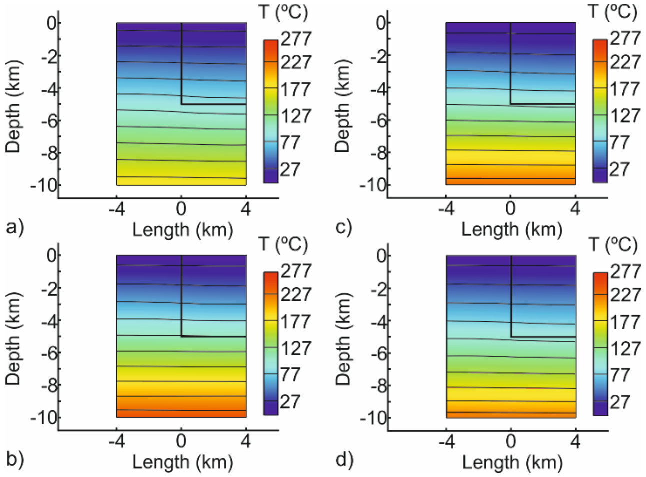

Fig. 2 2D temperature distribution simulated below Kuujjuaq. a) constant and b) to d) temperature-dependent thermal conductivity

4. Conclusions

Thermal conductivity decreases as a function of increasing temperature. This has an influence on the evaluation of the temperature distribution at depth. A non-temperature-dependent model suggests a temperature of 100 °C at 5 km depth. This value increases up to 113 ° C for a temperature-dependent model. The different relationships to describe the behavior of thermal conductivity as a function of temperature are observed to have an influence on the simulation results.

This new evaluation of the temperature field below Kuujjuaq predicts suitable temperatures to directly use the deep geothermal resources. Space heating might be a viable option to offset the diesel consumption and provide energy security to the communities north of the 49° parallel in the context of Nunavik.

Acknowledgments

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