EFFECT OF CONFINING PRESSURE ON POROSITY AND THERMAL CONDUCTIVITY: AN EXAMPLE FROM CRYSTALLINE ROCKS OF KUUJJUAQ, CANADA

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Abstract

The aim of this work is to obtain an experimental relationship that best describes the effect of confining pressure on primary porosity, and indirectly evaluate the influence of confining pressure on thermal conductivity. The results reveal that primary porosity decreases logarithmically as a function of confining pressure. For the pressure range 2.8 to 48.3 MPa, thermal conductivity indirectly evaluated increases less than 10 %. Considering the effect of confining pressure and temperature on thermal conductivity, a temperature of 104 ºC at 5 km is simulated below Kuujjuaq (QC, Canada).

1. Introduction

The application of pressure on a rock sample leads to compression of the interstitial pore spaces (e.g., Hui-yuan et al. 2016) and, consequently, to a decrease of the primary porosity. This, in turn, causes an increase in the thermal conductivity of the geological materials.

In the present work, the primary porosity of rock samples was evaluated at confining pressures ranging from 2.8 to 48.3 MPa. Then, the effect of confining pressure on thermal conductivity was indirectly inferred considering the relationship between porosity and thermal conductivity.

2. Methods

Primary porosity of 24 crystalline rock samples was evaluated by a combined gas permeameter-porosimeter AP-608 from Core Test (e.g., Raymond et al. 2017). The analyses follow Boyle's law. This law states that the pressure exerted by a given mass of an ideal gas is inversely proportional to the volume it occupies (Raymond et al. 2017 and references therein). This instrument can evaluate the hydraulic properties at confining pressures ranging from 2.8 to 68.9 MPa.

Following the evaluation of porosity at different confining pressures, the results were fit to the following functions:

$$\phi(Pc) = \phi_0 + aPc \tag{1}$$

$$\phi(Pc) = \phi_0 Pc^{-a} \tag{2}$$

$$\phi(Pc) = \phi_0 \exp^{-aPc} \tag{3}$$

$$\phi(Pc) = a\ln(Pc) + \phi_0 \tag{4}$$

where Φ (%) is primary porosity, Pc ($\times 10^6$ Pa) is confining pressure and a ($\times 10^6$ Pa^{-1}) is an experimental coefficient that controls the confining pressure dependence of the porosity. The subscript *0* stands for porosity at ambient pressure conditions (1 atm = 0.1 MPa).

The following mixing models were used to describe the relationship between thermal conductivity and porosity:

$$\lambda_{\text{bulk}} = \phi\lambda_{\text{fluid}} + (1-\phi)\lambda_{\text{solid}} \tag{5}$$

$$\frac{1}{\lambda_{\text{bulk}}} = \frac{\phi}{\lambda_{\text{fluid}}} + \frac{(1-\phi)}{\lambda_{\text{solid}}} \tag{6}$$

$$\lambda_{\text{bulk}} = \lambda_{\text{fluid}}^{\phi} \times \lambda_{\text{solid}}^{(1-\phi)} \tag{7}$$

where λ (W m^{-1} K^{-1}) is thermal conductivity. The subscripts ***bulk***, ***fluid*** and ***solid*** stand for the bulk thermal conductivity, the thermal conductivity of the fluid phase filling the pores, and the thermal conductivity of the solid phase, respectively. Considering the previous relationships, the effect of confining pressure on thermal conductivity is indirectly inferred.

3. Results

The results reveal a decrease of primary porosity with the increasing confining pressure. On average, the primary porosity decreases more than 50 % for all the lithologies analyzed (**Table 1**). These results were fit to Eqs. (1) to (4) and the best-fit is given by the logarithmic function (**Fig. 1**), with a coefficient of determination (R^2) varying from 0.98 to 1.00.

Paragneiss:

$$\phi(Pc) = -0.5\ln(Pc) + 2.81 \tag{8}$$

Diorite-gabbro:

$$\phi(Pc) = -0.3\ln(Pc) + 2.05 \tag{9}$$

Table 1 Porosity as a function of confining pressure and depth

Pc ($\times 10^6$ Pa)	Φ (%)		
	Paragneiss (n = 8)	Diorite-gabbro (n = 9)	Tonalite-granite (n = 7)
2.8	2.25	1.62	2.07
4.8	2.11	1.56	1.95
6.2	1.99	1.48	1.83
10.3	1.71	1.31	1.61
20.7	1.36	1.04	1.31
34.5	1.12	0.86	1.12
48.3	0.94	0.72	0.97
Variation ratio	58 %	56 %	53 %

n – number of samples

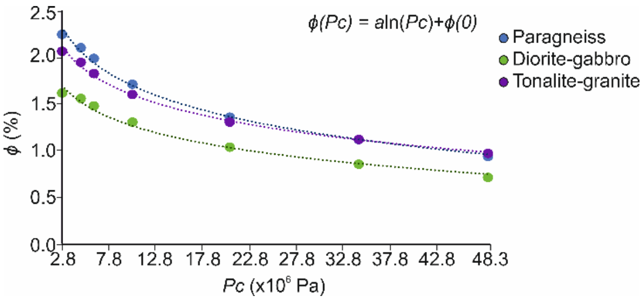

Fig. 1 Porosity as a function of confining pressure

Tonalite-granite:

$$\phi(Pc) = -0.4\ln(Pc) + 2.53 \quad (10)$$

Considering the geometric mean to describe the relationship between thermal conductivity and porosity, then, by integration of Eq. (4) in Eq. (7), a general function is obtained to indirectly infer the effect of confining pressure on thermal conductivity:

$$\lambda_{\text{bulk}} = \lambda_{\text{fluid}}^{\left[a\ln(Pc)+\phi_0\right]} \times \lambda_{\text{solid}}^{\left(1-\left[a\ln(Pc)+\phi_0\right]\right)} \quad (11)$$

The results reveal a less than 10 % increase of thermal conductivity for the confining pressure range of 2.8 to 48.3 MPa (**Fig. 2**).

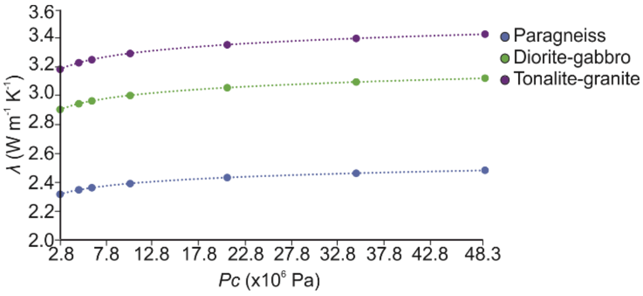

Fig. 2 Thermal conductivity as a function of confining pressure

The relationship between thermal conductivity and confining pressure was implemented in a finite element COMSOL Multiphysics model as an interpolation function to simulate heat conduction in the crust.

The results reveal that at 5 km, a temperature of 80 ºC is expected to be find below Kuujjuaq (**Fig. 3b**). Neglecting the effect of confining pressure, the temperature at 5 km is predicted to be 90 ºC (**Fig. 3a**).

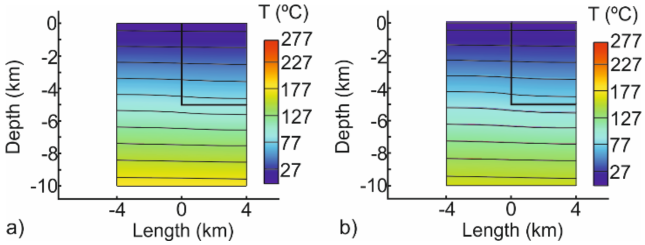

Fig. 3 2D temperature distribution simulated below Kuujjuaq (see Miranda et al. (this volume) for further details on the numerical model). a) constant and b) pressure-dependent thermal conductivity

In turn, if the temperature and confining pressure dependence on thermal conductivity are considered, the temperature simulated below Kuujjuaq increases by 9 %. In this case, a temperature of 104 ºC is predicted at 5 km depth (**Fig. 4**)

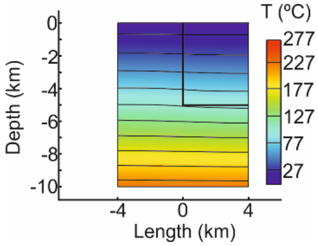

Fig. 4 2D temperature distribution simulated below Kuujjuaq

4. Discussion

Primary porosity decreases logarithmically as a function of confining pressure. These results agree with the work of Hui-yuan et al. (2016). The decrease in the primary porosity leads to an increase of thermal conductivity. For the range of confining pressure analyzed, this increase is less than 10 %. Clauser and Huenges (1995) present a data compilation on the effect of confining pressure on thermal conductivity for granite and metamorphic rocks. These authors observed a 10 % increase on thermal conductivity within the pressure range 0 – 500 MPa.

The obtained results indicate that, for low-porosity rocks, the effect of confining pressure on thermal conductivity is minimal when compared with the influence of temperature (more than 40 %; see Miranda et al. (this volume)). Assuming only the pressure influence on thermal conductivity, at 5 km depth, a temperature of 80 ºC is predicted. If only the effect of temperature is considered, then this value increases to 105 – 113 ºC (Miranda et al. (this volume)). However, considering both temperature and pressure dependence on thermal conductivity, then, at 5 km depth, the temperature field simulated is 104 ºC.

5. Conclusions

This work shows that 1) primary porosity decreases logarithmically as a function of confining pressure, 2) the effect of confining pressure is stronger on primary porosity than in thermal conductivity, and 3) thermal conductivity, indirectly evaluated, increases by less than 10 % as a function of the confining pressure. Considering the effect of confining pressure and temperature on thermal conductivity, a temperature of 104 ºC at 5 km was simulated with a numerical heat conduction model below Kuujjuaq.

Despite the high uncertainty due to subsurface data gap, the simulated temperatures indicate potential direct use of geothermal resources to offset diesel consumption in the Canadian off-grid communities.

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