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The Geothermal Open Laboratory: a free space to measure thermal and hydraulic properties of geological materials

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Introduction

Analytical and numerical models to simulate and predict the behavior of geothermal systems of all kinds, from geothermal heat pumps to high temperature hydrothermal reservoirs, rely on the knowledge of thermal and hydraulic properties of host rocks. Such natural systems are highly complex with ground heterogeneity that is difficult to characterize. Nevertheless, rock samples taken from surface outcrops and drilled cores can be analyzed to determine their thermal and hydraulic properties in order to picture subsurface heterogeneity that will affect geothermal system performances. From this perspective, a new laboratory, named the Geothermal Open Lab or the LOG (*Laboratoire ouvert de géothermie*), has been developed at the *Institut national de la recherche scientifique* (INRS) in Quebec City to measure thermal and hydraulic properties of rock samples.

The LOG operates in an open collaborative way, like open-source software, for researchers to make free analysis in exchange of sharing their results in a common database. Research groups interested have to supply their own work force to do their analysis in a supervised environment, where access to high-tech instruments is offered. All analysis results are compiled in a database maintained by the INRS and becoming publicly available three years after the analysis have been performed, generating common knowledge about rock thermal and hydraulic properties.

The analytical capacity of this new laboratory is described in this abstract, with the objective of developing interest among researchers of the UNESCO International Geoscience Program group 636 and other potential users. The following summarizes the laboratory methods that have been implemented at the LOG.

Guarded heat flow meter

A FOX-50 guarded heat flow meter from Laser Comp is installed to perform thermal conductivity analysis of core plug samples in steady state at controlled temperature (Figure 1a). The instrument consists of parallel round conducting plates with a guard insulation cylinder. Plates are equipped with thermoelectric Peltier elements and water flow cooled heat sink to control temperature. The sample is placed between the plates maintained at given temperature to establish a steady-state heat transfer rate across the sample. Heat flow transducers evaluate the heat flux based on the electric signal of the elements to deduced the temperature gradient and calculate the thermal

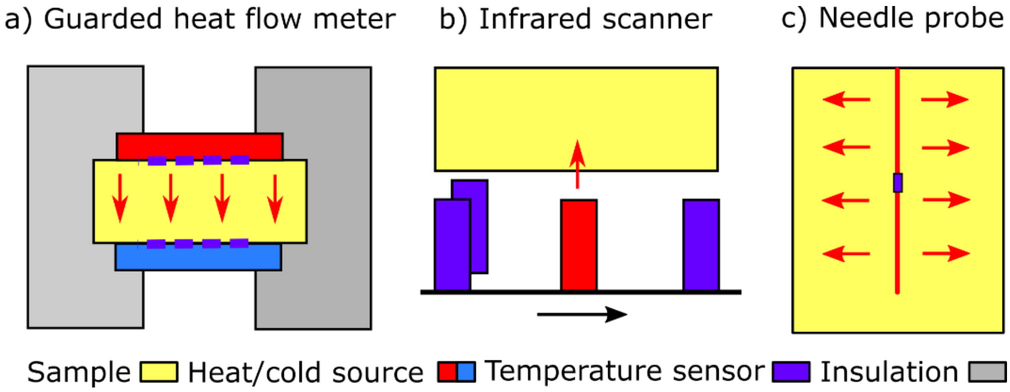

Figure 1. Instruments to measure thermal conductivity available at the LOG.

conductivity (Filla and Slifka, 1997).

Cylindrical shaped samples with a diameter of 25 to 61 mm and a maximum thickness of 25 mm can be analyzed with the guarded heat flow meter to determine thermal conductivity under a range of 0.1 to 10 W m^{-1} K^{-1} at controlled temperature from -10 to 190 °C. Analysis can be performed from both dry and water saturated samples. The flatness and parallelism of a sample upper and lower face should be within 0.03 mm and 0.1 mm, respectively, to avoid potential thermal resistance at the contact with heating plates. Sample faces must be ideally polished to ensure flatness and parallelism. Liquids and unconsolidated sediments can be analyzed in cells with conductive upper and lower plates. The accuracy of the thermal conductivity evaluation is ± 3 % and the accuracy of the temperature control is 0.01 °C. The guarded heat flow meter allows to establish a vertical steady-state heat flow across the whole sample in other to determine its bulk thermal conductivity from permafrost to geothermal reservoir temperature conditions. The volumetric heat capacity of the sample can additionally be deduced from the temperature measurements during the transient heat transfer period before the sample temperature reach equilibrium.

Thermal conductivity scanner

A thermal conductivity scanner with an infrared heat source made by LGM Lippmann is used for transient thermal conductivity and diffusivity analysis of hand specimens and core samples at room temperature (Figure 1b). The instrument relies on the optical scanning technique developed by Popov (1999) to conduct the analysis. A moving optical head with an infrared heat source and temperature sensors can scan thermal properties along the sample (Jorand et al., 2013). The temperature sensors are located before and after the heat source to measure unperturbed, or cold, and perturbed, or hot, temperature from which the thermal conductivity and diffusivity are deduced according to comparative measurements performed on reference samples placed before and after the rock sample.

Flat and cylindrical sample faces of 40 to 500 mm in length can be analyzed along a scan line that have been painted with black enamel to ensure proper infrared absorption to heat the sample. The range of thermal conductivity and diffusivity evaluation are 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. The spatial deviation of the sample surface must not exceed ± 5 mm, which is typically achieved by cutting the rock sample with a diamond trim saw and an end face grinder. A dry rock sample is placed between reference materials and measurements can be achieved at a scanning speed of 5 mm s^{-1}. The transient heat transfer analysis achieved with the thermal conductivity scanner has a small depth of penetration and allows a local evaluation of thermal properties along the scan line to identify potential heterogeneity.

Needle probe

A KD2 Pro needle probe from Decagon is available for transient thermal conductivity and diffusivity analysis at room temperature (Figure 1c). The probe encloses several heating needles that can be inserted in liquids, unconsolidated sediments and solid rocks, provided that a thin hole has to be drilled in the sample to perform the measurements. A temperature sensor is located inside each needle to monitor temperature at the sample contact and calculate thermal conductivity from the transient temperature perturbation (Raymond et al., 2017). Thermal diffusivity can be evaluated with a dual needle, one of which is heating while the other is monitoring temperature to evaluate heat storage across the sample (Bristow et al., 1994).

The needles available are suitable for analysis of most common geological materials under dry and water saturated conditions (Table 1). A thermal grease compound has to be spread out on the needle to minimize thermal resistance at the sample contact when analyzing rocks. The heat pulse transmitted to the sample has a limited depth of penetration such that analysis reveals punctual values that are representative of the sample when homogenous. The method is best suited for unconsolidated sediments, in which the needle can be easily pushed inside. Care should be taken not to change the sample original density and water saturation that can greatly affect the thermal properties of unconsolidated sediments.

Table 1. Characteristics of needles available with KD2 Pro.

Needle	KS-1	TR-1	SH-1 (dual)	RK-1
Material	Liquid and paste	Soft solid (soil)	Soft solid (soil)	Hard solid (rock)
Diameter (mm)	1.3	2.4	1.3	3.9
Length (cm)	6	10	3	6
Thermal conductivity range (W m^{-1} K^{-1})	0.02-2.00	0.1-4.0	0.02-2.00	0.1-6.0
Thermal conductivity accuracy (%)	5	10	10	10
Thermal diffusivity range (m^2 s^{-1})			1.0×10^{-7} 1.0×10^{-6}	
Thermal diffusivity accuracy (%)			10	

Combined gas permeameter and porosimeter

An AP-608 automated permeameter-porosimeter from Core Test Systems is used for the evaluation of hydraulic properties of rock samples (Figure 2a). Porosity analysis is made according to Boyle's law, where the pressure exerted by a given mass of an ideal gas is inversely proportional to the volume it occupies (American Petroleum Institute, 1998). Gas with a reference volume at a given pressure is allowed to flow in a core chamber including the sample where pressure will equilibrate. The volume of solids in the rock is determined from the initial pressure of the gas chamber and the core chamber pressure at equilibrium, assuming a constant temperature and number of gas moles. The sample volume is evaluated with a digital caliper to finally calculate the volume of voids and porosity. A separate grain volume chamber is additionally available to evaluate density of solid grains. Permeability analysis relies on the transient pressure decay method (American Petroleum Institute, 1998). When the gas is allowed to flow in the rock sample, the pressure is monitored to infer the permeability using Darcy's law. Gas slippage effect, where gas permeability of porous media becomes a linear function of pressure since gas molecules do not adhere to the solid pore walls like liquid molecules, can be taken into account with the Klinkenberg correction to calculate the permeability to liquid.

Cylindrical core plug samples with a diameter of 25.4 mm or 38.1 mm and a length of 25.4 to 101.6 mm can be analyzed at room temperature. Porosity evaluation is made at a 13.8 bar within a range of 0.1 to 40 %. Permeability analysis is achieved with a pressure pulse of 6.9 to 17.2 bar under confining pressure of 34.5 to 689.5 bar within a range of 0.001 mD to 10 D. Air and helium can be used for the gas source. This transient method has been put in place to evaluate hydraulic properties under reservoir pressure or under the effect of pressure increase when fracking rocks to develop reservoirs.

Portable gas permeameter

A PPP-250 portable probe permeameter from Core Laboratories is further used to measure gas permeability of core samples directly in the core box or on flat outcrop surfaces (Figure 2b). The permeability is determined with the pressure decay method similarly to the gas permeameter described above, except that the gas flow from the probe tip pressed again the rock surface (Filomena et al., 2014). The compact unit includes a gas reservoir allowing field measurements without a gas source.

An initial pressure up to 1.7 bar is injected in the rock mass and the gas, compressed air, is allowed to flow in the rock to monitor the pressure decrease. The permeability evaluated from this pressure decay has to be in a range of 0.001 mD to 5 D. This additional transient permeability technique provides greater flexibility when measurements have to be performed outside the laboratory. For example, the probe can be used on an outcrop to evaluate the permeability of fractured versus unfractured zones. However, Klinkenbeg correction can't be performed with this instruments where analysis are carried out at the same pressure.

Conclusions

The Geothermal Open Lab or the LOG has major analytical capacities to evaluate thermal and hydraulic properties of geological materials constituting geothermal systems. The idea is to combine the instruments to broader characterization possibilities. For example, the guarded heat flow meter can be used to evaluate the bulk thermal conductivity of a sample further analyzed with the infrared scanner to identify possible heterogeneity affecting the bulk value. High temperature measurements can also be made with the guarded heat flow meter to verify the impact of temperature increase, which is not possible to achieve with the infrared scanner. Additionally, the INRS has a tomodensitometry laboratory with a medical computed tomography scanner (CT-scan), although not operated in an open mode, to verify density variation of various samples. Results from infrared and X-ray scanners can be combined to evaluate the links between rock density and thermal conductivity.

The combined permeameter-porosimeter is another instrument to use with the CT-scan to identify the relationships between density, porosity and permeability distribution. Local measurements can be achieved with the combined permeameter-porosimeter than can be extrapolated from density functions deduced with the CT-scan over long core distances. Then, the portable permeameter can be used to validate results in the field or at the core shack.

The operation of the LOG in an open fashion will help to build common knowledge on rock thermal and hydraulic properties that are, not only useful for geothermal studies, but any research involving subsurface flow and heat transfer related to groundwater, environment, oil and gas and ground stability. The authors have too often come across brilliant groundwater flow and heat transfer modeling studies with limited outreach because simulation results were unfortunately based on poorly constrained literature properties. The LOG is intended to fill this gap by providing the instruments to measure thermal and hydraulic properties used by geothermal system modelers and other scientists to eventually improve the literature with greater data content share to the scientific community.

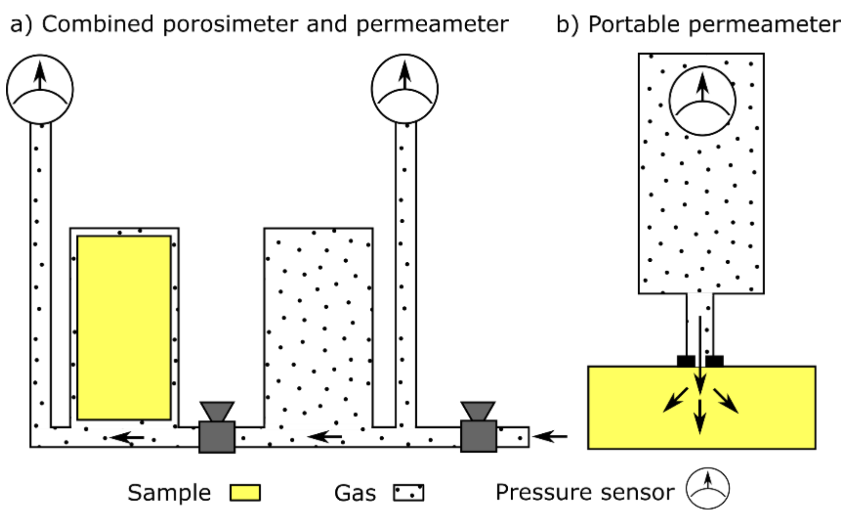

Figure 2. Instruments to measure porosity and permeability available at the LOG.

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