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Thermal conductivity and porosity maps for different materials: A combined case study of granite and sandstone

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ABSTRACT

Thanks to thermal conductivity maps, obtained from Optical Scanning method, and porosity maps, inferred from thermal conductivity maps, we have studied petrophysical heterogeneities commonly present in a granitic and sandstone geothermal reservoir (fault zone and permeable layers, respectively). The maps allowed determination of thermal conductivity and porosity variation to millimeter resolution, at a core scale. They permitted precise quantification and determination of the size of petrophysical heterogeneities (thermal conductivity and porosity) induced by rock variability.

1. Introduction

In the current context of commitment to sustainable and renewable energy, many countries worldwide are developing geothermal energy (Dickson and Fanelli, 2003; Lund et al., 2011; Bertani, 2012). To enhance and ensure the economic and technical viability of the heat exchanger at depth, it appears important to improve the knowledge of thermal and hydraulic properties of the targeted reservoir and their behaviors during the exploitation period (see for example Birsch, 1966; Cermak and Rybach, 1982; Haenel et al., 1988; Clauser and Huenges 1995; Clauser 2006; Hartmann et al., 2008). Indeed, these properties play a major role in the planning of geothermal installation and in geothermal modeling.

Through a geothermal reservoir exchanger, fluid flows occur in the fractures and faults connected network and in different sedimentary levels of high permeability (Haffen et al., 2013; Siffert et al., 2013). These fluids present different types of disequilibrium with respect to the surrounding rocks, as well to temperature and chemical composition. Indeed, interaction processes between fluids and rock, which occur over time in the porous space connected to the main fluid flow zone (mass transfer induced by dissolution and precipitation phenomena or mechanical displacement of clayed particles), can provoke damage to the heat exchanger by modifying its permeability and also affect the surface power plant (Norton and Knapp, 1977; Norton, 1979; Seibt and Kellner, 2003; Ungemach, 2003; Fritz et al., 2010; Civan, 2011; Meier et al., 2014).

Thus, thermal conductivity and porosity maps appear to be two key parameters, since they allow the improvement of the targeted rock characterization, notably from information (quantification and size) about potential rock heterogeneities.

Various experimental techniques allowed the characterization of the thermal conductivity and porosity of rock samples (Zinszner and Pellerin, 2007; Tritt, 2004). We developed a new non-destructive method based on Optical Scanning (Popov et al., 1999), to quickly map the thermal conductivity and porosity of samples. We present the acquired 2D thermal conductivity maps and the computed 2D porosity maps.

In this paper, we present results for two kinds of rock: granite and sandstone, which both have specific structures (fractures and sedimentary heterogeneities, respectively). These rocks are of special interest because, for continental Europe, high enthalpy geothermal targets are located in the deep part of the sedimentary basin, its basement and its lower levels, including the bottom of the sedimentary cover, which is generally sandstone (Genter et al., 2003; Bourquin et al., 2011).

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2. Geological setting and thermal conductivity/porosity maps elaboration

2.1. Sample description

The selected samples are expected to illustrate two kinds of fluid flow networks in deep geothermal targets. First, a granite sample affected by a fracture zone with quartz infilling at the edge of an open fracture is a kind of structure currently described in granitic geothermal fields (Géraud et al., 2010). Second, a sandstone sample is analyzed, where a sedimentological heterogeneity was induced by grain size variation.

The granite sample (K195-4777) was taken from the EPS1 borehole, part of the deep experimental geothermal site of Soultz-sous-Forêts (France) in the Upper Rhine Graben (Genter and Traineau, 1992; Rosener, 2007) (Fig. 1a). The sample is located approximately 2162 m deep, in a granite zone that corresponds to a silicified/cataclased hydrothermal alteration facies (Rosener, 2007). This allows the different compartment typically encountered in fault zones to be studied: the protolith, the damaged zone and the fault core (Caine et al., 1996; Géraud et al., 2010; Faulkner et al., 2010). The sample is divided into three zones (Fig. 1a). Zone 1 corresponds to a damaged zone and is an altered zone composed of massive orange feldspar (orthoclase) associated with altered feldspar, some small secondary quartz and black mica. It has an increase in porosity due to an alteration process induced by hydrothermal fluids. Zone 2 is characterized by a sizable concentration of secondary quartz and hardly any altered feldspar. It corresponds to the protolith. Zone 3 shows a partially sealed localized quartz fault core.

The sandstone sample (EPS1_6_1) also came from the EPS1 borehole (Haffen, 2012) (Fig. 2a), and was extracted at a depth of approximately 1214 m, from the Buntsandstein sandstones formation: "Grès Vosgiens" facies (Vernoux et al., 1995; Bourquin et al., 2006). The petrographic facies corresponds to clayed coating sandstone alternating with clean sandstone (see Haffen, 2012; for details). The sample can be divided into two zones (Fig. 2a): zone 1 is composed mainly of fine to very fine dark brown grained sandstone, and zone 2 is mainly made of medium to fine brown grained sandstone. A small fault is marked by a gap of approximately 5 mm, which is sealed off by extremely thin barite precipitation.

2.2. Measurement techniques: thermal conductivity scanner (TCS)

Optical Scanning measurements performed with a TCS (Popov et al., 1999; Popov et al., 2003) deliver a large set of thermal conductivity values faster than classical laboratory techniques, such as with a divided-bar or a lining source (Sass et al., 1971, 1984). The Optical Scanning apparatus corresponds to a mobile block composed of two temperature sensors on either side of a constant and continuous heat source. These three fixed elements are lined-up on the mobile block, parallel to the mobile displacement axis. The block moves under a rail on which the sample to be measured had been previously placed. Heat source and temperature sensors move at the same relative speed (TCS mobile block velocity: 4.99 mm s^{-1}) along the scanning surface, which is maintained at a constant distance from both sensors. Thus, measuring the sample temperature before and after its heating is rendered feasible. These data, associated with those of the two standards situated either side of the measured sample and having a thermal conductivity known to be close to that of the sample, allow calculating the absolute thermal conductivity of the sample to become possible. This technique therefore permits the obtainment of a profile of thermal conductivity of the sample along a scan line, with a resolution of 1 mm. The scan line is at a maximum of 500 mm, due to the length of the apparatus, while the relative measurement error is approximately 3% of the measured value (Popov et al., 1999). The room where measurements were carried out was kept at a constant temperature (20 °C ± 1 °C). During the measurements, the increase in sample temperature was limited to 3 °C, ranging from 20 ± 1 °C to a maximum of 23 ± 1 °C. A brief cooling time was systematically imposed between two scan lines to restrict the heating of the sample and of the standards. Thermal conductivity variations induced by the heating of the sample during the measurement were neglected, since at this temperature range the thermal conductivity variation is inferior to the measurement error (Vosteen and Schellschmidt, 2003).

2.3. Thermal conductivity and porosity map

2.3.1. Method

Thermal conductivity in rocks depends mainly on three parameters (e.g. Farouki, 1981; Brigaud and Vasseur 1989; Clauser and Huenges, 1995; Midttomme and Roaldset, 1998): mineralogical composition, porosity and texture. Other parameters can also control the thermal conductivity of rocks as pore fluids properties and structural/textural properties of rocks including rock anisotropy The porosity of a rock can be estimated (Schärli and Rybach, 1982) at constant temperature and pressure, using comparisons between thermal conductivity values obtained for air- and water-saturated samples, while mineralogy and other microstructural parameters are taken as being constant. For each state, the geometric mean model based on mixing laws (Eq. (1), Clauser and Huenges, 1995) is considered, as follows:

$$\lambda = \lambda_f^{\Phi} \times \lambda_m^{1-\Phi} \quad (1)$$

where λ (W m^{-1} K^{-1}) is the effective thermal conductivity, λ_f (W m^{-1} K^{-1}) is the thermal conductivity of the fluid (air or water) present in the porosity (Φ (−)), and λ_m (W m^{-1} K^{-1}) is the thermal conductivity of the solid matrix.

For a sample, a first set of thermal conductivity measurements under air-saturated conditions and a second set of thermal conductivity measurements under water-saturated conditions are necessary and these lead to the porosity calculation (Eq. (2)) as follows (Pribnow and Sass, 1995; Pribnow et al., 1996; Surma and Geraud, 2003; Haffen, 2012):

$$\Phi = \frac{\ln\left(\lambda_{sat}\right) - \ln\left(\lambda_{dry}\right)}{\ln\left(\lambda_{wat}\right) - \ln\left(\lambda_{air}\right)} \quad (2)$$

where λ_{sat} (W m^{-1} K^{-1}) is the thermal conductivity of the water-saturated sample, λ_{dry} (W m^{-1} K^{-1}) is the thermal conductivity of the air-saturated sample, λ_{wat} is the thermal conductivity of water (0.6 W m^{-1} K^{-1}, Clauser and Huenges, 1995) and λ_{air} is the thermal conductivity of air (0.02 W m^{-1} K^{-1}, Clauser and Huenges, 1995).

Thus, to calculate porosity, we have considered a simplified case, without needing to build an empirical model (Somerton, 1992). Satisfying results were obtained with the applied mathematical model, based on a mixing law (Pribnow et al., 1996; Hartmann et al., 2005).

This mathematical model (Eq. (2)) was used to determine the mean porosity value from measurements of the thermal conductivity in both dry and wet samples. Here, we use the Optical Scanning method to measure the thermal conductivity. From these measurements and the experimental measurement protocol first proposed by Rosener (2007), we can build a 2D porosity map from 2D thermal conductivity maps. This approach let us observe millimeter scale variations of thermal conductivity and porosity for pluri-decimeter rock samples.