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Study cases of thermal conductivity prediction from P-wave velocity and porosity

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ABSTRACT

Laboratory measurements of porosity, P-wave velocity and thermal conductivity from samples from two geothermal reservoirs in France and Australia are compared to the predictions from different models involving mineralogical considerations, and effective medium theory models yields <10% error in dry and saturated conditions in the Australian aquifer, and <30% deviation under saturated conditions in the French reservoir. Thermal conductivity derived from models involving detailed mineralogy is in good agreement with laboratory-measured data. Possible explanations for minor discrepancies using SEM/XRD include the effects of secondary minerals (i.e. ±undetected carbonates and fine particles) and the hydration of clays.

1. Introduction

Assessing in situ heat transport properties in geological formations remains challenging from a scientific and a technical point of view. Most of the available datasets of thermal conductivity (TC) and diffusivity are based on empirical laws using various bulk measurements from logging tools and sometimes barely calibrated from sparse core measurements in the laboratory, if available at all (Brigaud et al., 1989, 1990; Demongodin et al., 1991; Revil, 2000; Abdulagatova et al., 2010). The rare models available in the literature either require a large amount of parameters (Singh et al., 2007; Tong et al., 2009) or are semi-empirical (e.g. Côté and Konrad, 2009), making TC predictions limited to very particular cases of study (Wang et al., 2006). These models results are therefore difficult to use in practical applications such as geothermal reservoirs management, underground waste disposal, CO_2 sequestration, heavy oil and gas hydrates.

Recently, Pimienta et al. (2014) reported a new TC model (PSED: Pimienta–Sarout–Esteban–Delle Piane; authors' name of this model), assuming that the TC of a porous and microcracked rock largely depends on the density and geometry of the microcracks. Their approach relied on the observed similar dependency of TC and elastic wave velocities (EWV) to confining pressure, and thus to pressure-dependent microstructural features such as microcracks. In the paper, the authors aimed at predicting the TC on clean sandstones dominated by quartz grains from measured elastic wave velocities (EWV). The strength of this new model is that only two input parameters are required to predict TC: porosity and P-wave velocity (V_P); both of which can be estimated from wireline logs and/or measured from rock samples in the laboratory. Therefore, this approach can be used to predict in situ TC, assuming that the entire target formation is also clean and monomineralic. In this predictive approach from Pimienta et al. (2014), TC and EWV parameters were modelled using effective medium theory (EMT). The predictive results were benchmarked against published experimental data from four quartz-rich sandstones (i.e. Berea Sandstone, Fontainebleau Sandstone, St-Peters Sandstone and Tensleep Sandstone) where V_P, V_S, porosity and TC under dry and water-saturated conditions are available (e.g. Woodside and Messmer, 1961; Zamora et al., 1993; Gomez et al., 2010; Lin et al., 2011). In particular, pressure dependent measurements of TC (Woodside and Messmer, 1961; Lin et al., 2011) and EWV (e.g. Tao et al., 1995; Mavko and Vanorio, 2010) on the well-known Berea Sandstone samples allowed validation of the microcracks control on EWV and TC responses.

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Accessing reservoir TC directly (in situ) is currently impossible. All the classical empirical laws to compute TC, mostly based on the geometrical mean of the Archie equation, require detailed knowledge of the mineralogy that is not trivial to access. The motivation behind this PSED model approach is to demonstrate the potential of commonly acquired porosity and V_P parameters from wireline log datasets or laboratory measurements (under or not in situ conditions) to predict TC. In turn, assuming a known dominant mineral content (quartz or calcite) within a rock formation with thermal conduction as a main mechanism of heat transport, prediction of TC would allow for instance to: (i) estimate and/or monitor with time the heat flow, (ii) extract temperature profile, (iii) evaluate the water saturation of the formation and (iv) access TC without appropriate core data.

In this contribution, the limitations of the TC model that assumes a monomineralic composition are tested on rock samples from two sandstone reservoirs, Soultz-sous-Forêts (EPS-1: Upper Rhine Graben, Eastern France) and Perth Basin (Cockburn-1, Gingin-1 & -2 and Pinjarra-1: Western Australia), for which extensive laboratory datasets are available: water, helium or mercury porosity, thermal conductivity, acoustic velocity and mineralogy. All these physical properties are measured under ambient conditions (22 °C, atmospheric pressure, 35–40% relative humidity) to test the model. Following description of the new methodology for predicting TC, the results (PSED) are compared to the conventional approach that involves derivation of the geometric mean from Archie's law (Woodside and Messmer, 1961), assuming (i) a pure quartz-matrix or (ii) where detailed knowledge of mineralogy is used to compute the TC of the matrix. The model predictions of TC are also compared to laboratory measurements of TC. These quartz-rich formations (volume fraction >69%) were expected to yield reasonable fit between measurements and predicted TC. However, deviations are still observed for the water-saturated rock samples. To test the relationship in disturbed conditions, i.e. with variable contents in non-quartz phases, the sandstone samples of the "Bundsandstein" formations from the EPS-1 borehole (Alsace, France) are selected. Primary minerals (K-feldspars) and secondary minerals (calcite and clays minerals, up to 43%) content, which have been recognized by X-ray diffraction measurements and petrological observations, are therefore investigated in the light of their impacts on the deviation of the PSED model from the measurements and Archie's model.

2. Rock samples characterization and investigation methods

2.1. Laboratory characterization

Core plugs were extracted from the cored sections of several wells: Gingin-1 and Gingin-2, Cockburn-1 and Pinjarra-1 in the Perth Basin Western Australia; and EPS-1 in the Upper Rhine Graben (URG), North-East of France. The simplified stratigraphy encountered by the wells and their location is illustrated in Fig. 1. The core plugs were analyzed in a series of laboratory tests that aimed at quantifying their thermal conductivity (TC), porosity, and ultrasonic P-wave velocity (V_P) under ambient laboratory conditions. Most of these experimental data are available in Delle Piane et al. (2013) for the Perth Basin and in Haffen et al. (2013) for the Upper Rhine Graben.

One hundred and sixteen samples were collected from 4 wells in the Perth Basin (Fig. 1a; Table 1) at depths ranging from 112 to 4460 m. The sample size from Gingin-1 & -2 wells is 38 mm in diameter and ±50 mm in length; and 25.4 mm in diameter and ±40 mm in length in Cockburn-1 and Pinjarra-1 wells. These samples represent five Jurassic sandstone-dominated formations of fluvio-deltaic to marine origin: the Yarragadee Formation (Formation top 319 m at Cockburn-1 well), the thin Cadda Formation (Formation top 1725 m at Cockburn-1 well), the Cattamarra Coal Measures (Formation top 1914 m at Cockburn-1 well), and Eneabba Sandstone and Lesueur Formations (only available in Pinjarra-1 well; Formation tops 1203 and 2373 m, respectively). A detailed review of the stratigraphy is available in Timms et al. (2014). The Lesueur Sandstone Formation is targeted as a potential for CO_2 geosequestration (Stalker et al., 2013; Olierook et al., 2014) whereas the Yarragadee Formation is an aquifer that has a potential for geothermal heat extraction (Reid et al., 2012).

Porosity of the Perth Basin samples was measured using an automated helium porosimeter AP-608 (Core Test Systems Inc.) at the lowest pore and confining pressures of 1.7 MPa and 3.4 MPa, respectively. Prior to each measurement the core plugs were drilled and trimmed into a cylindrical shape. The instrument precisely measures porosity in the range 0.1 to >40% with an accuracy <1%. In a standard test, a rock sample is loaded into the core holder and flooded with inert helium gas. Helium expansion is monitored and the pore volume (i.e. porosity) of the rock sample is calculated following Boyle's law:

$$V_1 = \frac{P_2 \times V_2}{P_1} \quad (1)$$

where V_1 is the volume of helium permeating the rock sample; P_2 and V_2 are the pressure and the calibrated volume of helium before being released into the sample; and P_1 is the pressure of gas after sample infiltration.

The plugs from Cockburn-1 were subsequently cut along their axis with one half used for thin section preparation and mineralogy analysis (Timms et al., 2012, 2014); and the other half used to measure TC under dry and water-saturated conditions using an Optical Thermal Scanner (OTS; Popov et al., 1999) at the School of Earth Sciences, Melbourne University. The OTS method was introduced and developed by Yuri Popov in 1983. It allows for high-precision non-destructive non-contact measurements of thermal conductivity over a representative volume of rock, full core, and single crystals of minerals. Intensive measurements on more than 90,000 cores covering more than 200 rock types and crystals from various locations all over the world demonstrated the accuracy (3% within a range of 0.2–25 W/m/K) and precision of this tool (e.g. Popov, 1997; Popov et al., 1999).

The TC of samples from the three other Perth Basin wells was measured along the core axis similarly to Cockburn-1 samples, before extracting a thin layer at the end of each cylinder for thin section preparation and measurements of modal mineralogy from point counting (Timms et al., 2014). The Point counting method is based on optical photomicrographs acquired on each thin section (spatial resolution >2 μm) with a Zeiss Axio Imager II. The modal mineralogy is recorded from point counting from JMicroVision Ltd. (Roduit, 2006; Timms et al., 2012). Note that such method cannot access the clay types and yields poor results for clay particle sizes <2 μm. Only Gingin-2 samples were not analyzed for mineralogy. Samples were immersed in water and held under vacuum for 24 h prior to measurements to constrain TC for water-saturated conditions.

Water porosity was also estimated on the halved plugs by measuring the difference in weight of the samples before and after water saturation; porosity ($\o_{ev}$) can then be estimated as follows:

$$\phi_{ev} = \frac{V_{pore}}{V_{bulk}}; \quad V_{pore} = \frac{M_{sat} - M_{dry}}{\rho_W} \quad (2)$$

where V_{pore} is the pore volume (in cm^3); V_{bulk} is the total volume of the sample (in cm^3); M_{sat} is the mass of the water-saturated sample (in g); M_{dry} is the mass of the dry sample (in g); and ρ_W is the density of water equal to 1 g/cm^3 at room condition (1 atmosphere and 22 °C).