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Comparison of thermal and elastic properties of sandstones: Experiments and theoretical insights

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ABSTRACT

We measured P-wave velocity, thermal conductivity and thermal diffusivity on 26 sandstone samples under dry and water-saturated conditions. Subsequently, we compared these measurements with predictions by frequently used models.

Overall, these three properties decrease with porosity and increase with water saturation. Comparing data sets and models, we distinguish three main groups of sandstone samples: From the difference in the intrinsic elastic and thermal properties of the dominant mineral, two tendencies attributed to either quartz or another rock forming mineral are identified, which separate ***class 1*** sandstone and samples from ***class 2*** sandstones. Within ***class 1*** clean sandstones, a sub-class (***sub-class 1a***) consists of similarly porous samples having different elastic and thermal properties. Based on elasticity, we attribute this effect to microcracks or grain contacts in the samples. While this feature does not affect the total porosity, it affects all of three physical properties strongly and in a similar way. Additionally, we define a second sub-class (***sub-class 1b***) for Fontainebleau sandstone with porosities above 13%. For these four samples, the effect of water saturation on the elastic and thermal properties is different.

1. Introduction

Information on thermal rock properties is important for many applications ranging from the production of geothermal energy or hydrocarbons (e.g. heavy oils), over subsurface management (e.g. nuclear waste repositories) to civil engineering (e.g. heat transfer or insulation in buildings). In particular, this kind of information is of paramount importance for the assessment and production of geothermal energy (e.g. Clauser and Huenges, 1995; Clauser, 2006; Timms et al., 2012; Huenges et al., 2013; Rühaak et al., 2015). In response to the growing demand of energy, particularly renewable green energy, potential geothermal reservoirs have been studied worldwide over the last decade (e.g. Förster and Merriam, 1999; Fuchs and Förster, 2010; Timms et al., 2012; Huenges et al., 2013; Rühaak et al., 2015; Gu et al., 2017; Mielke et al., 2017).

Since rocks at depth have a low permeability, heat flow is dominated by conduction, which is governed by thermal conductivity (e.g. Förster and Merriam, 1999; Beardsmore and Cull, 2001; Clauser, 2011a,b). Thermal conductivity cannot be measured directly at the field scale. Therefore, a prediction from other measurable properties has been proposed in several studies (e.g. Griffiths et al., 1992; Zamora et al., 1993; Revil, 2000; Popov et al., 2003; Ozkahraman et al., 2004; Kazatchenko et al., 2006; Gegenhuber and Schön, 2012, 2014; Pimienta et al., 2014b; Esteban et al., 2015; Gu et al., 2017). However, most of this work relies on empirical relations linking these properties to thermal conductivity while ignoring factors such as rock type, mineral content or microstructure (e.g. Wang et al., 2006). Many factors influencing thermal conductivity have been discussed in the literature (summarized, e.g. by Clauser, 2011a,b): Thermal conductivity depends largely on mineral content (e.g. Pribnow and Umsonst, 1993; Torquato, 2001; Hartmann et al., 2005; Sundberg et al., 2009; Tarnawski et al., 2009; Fuchs and Förster, 2010), porosity (e.g. Ozkahraman et al., 2004; Giraud et al., 2007; Tong et al., 2010), and saturating fluid (e.g. Walsh and Decker, 1966; Zimmerman, 1989; Jorand et al., 2011). Moreover, the quality and geometry of the contact between the grains is a major influencing factor (e.g. Revil, 2000; Côté and Konrad, 2009; Jougnot and Revil, 2010). Last but not least, thermal conductivity varies with temperature (e.g. Abdulagatova et al., 2009, 2010; Vosteen and Schellschmidt, 2003) and pressure (e.g. Woodside and Messmer, 1961; Abdulagatova et al., 2009, 2010; Lin et al., 2011).

Most of the existing models rely on semi-empirical relations adapted to a given rock type. This may result in large uncertainties of the

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predictions (e.g. Wang et al., 2006; Hartmann et al., 2005; Fuchs et al., 2013; Rühaak et al., 2015; Fuchs and Balling, 2016). For instance, thermal conductivity of sandstones either dry or water-saturated was reported to range from 0.9 W m^{-1} K^{-1} to 6.5 W m^{-1} K^{-1} (Cermak and Rybach, 1982; Mielke et al., 2017). The causes for this wide range in thermal conductivity are not yet fully understood, and more insight is required on the dependence of the thermal properties on the ruling rocks parameters (e.g. Wang et al., 2006). Here, we want to account for various parameters that affect thermal rock properties and to assess their relative importance. Motivated by their similar dependencies with the well-studied elastic rock properties (e.g. Zamora et al., 1993; Ozkahraman et al., 2004; Kazatchenko et al., 2006; Gegenhuber and Schön, 2014; Pimienta et al., 2014b; Esteban et al., 2015), we perform a systematic comparative study on the effects of porosity, microstructure and saturation on both thermal and elastic rock properties on identical samples. To this end, we measure 26 sandstone samples under dry and water-saturated conditions. We interpret the results by (i) comparing the measured thermal and elastic properties; and (ii) inspecting their consistency with physical models chosen to account for the same effects.

2. Material & methods

We selected samples from sandstone as a widespread reservoir rock for our laboratory tests. For measuring, we used the optical scanning method for thermal properties and a standard pulse-transmission technique for P-wave velocity.

2.1. Rock samples

In our laboratory experiments, we study the effects of different rock parameters on the thermal properties. As the thermal conductivity of quartz, approximately 7.7 W m^{-1} K^{-1} (e.g. Horai, 1971), is twice that of any other common mineral, we expect to observe any effects best for sandstones. Moreover, because sandstones in most case do not consist exclusively of quartz, we also qualitatively discuss the influence of other minerals. Therefore, we distinguish in the following between pure quartz sandstones (***class 1***) and sandstones with significant amounts of other minerals than quartz (***class 2***).

2.1.1. Class 1 sandstones: fontainebleau sandstone

Fontainebleau sandstone is a well-known reference rock in rock physics and rock mechanics (e.g. Bourbie and Zinszner, 1985; Zamora et al., 1993; Schubnel et al., 2007; Gomez et al., 2010; Duda and Renner, 2013; Pimienta et al., 2014a, b) because it is a clean sandstone (i.e. quartz content above 99%) with randomly oriented and sorted grains of approximately 200 μm diameter (e.g. Duda and Renner, 2013). Hence, samples of this rock may be considered as homogeneous and isotropic at the sample scale (e.g. Pimienta et al., 2015a). As shown by Bourbie and Zinsner (1985), the rock covers a wide range of porosity (2% – 20%) and permeability (10^{-19} m^2 – 10^{-12} m^2). The varying degrees of porosity and permeability correlate to variable degrees of cementation (Bourbié and Zinszner, 1985; Guéguen and Palciauskas, 1994; Pimienta et al., 2014a). Moreover, rock samples show a varying degree of microcracking, independent of their porosity (e.g. Pimienta et al., 2015a, b; Pimienta et al., 2016a). This aspect results in very different elastic properties from one sample to the other along with a strong dependence on confining pressure (e.g. Walsh, 1965).

2.1.2. Class 2 sandstones

Class 2 consist of sandstones having a significant amount of rock-forming minerals other than quartz: Anröchter Grün sandstone (Fig. 1a), Herdinger sandstone (Fig. 1b), Odenspieler graywacke sandstone (Fig. 1c), Obernkichner sandstone (Fig. 1d), Wilkenson sandstone (Fig. 1e), Bentheimer sandstone (Fig. 1f) and Berea sandstone (Fig. 1g). The Anröchter Grün, Herdinger, Odenspieler (e.g. Grabert, 1967), Obernkichener (e.g. Mayr and Burkhardt, 2006), and Bentheimer (e.g. Louis et al., 2007; Blöcher et al., 2014; Pimienta et al., 2017) sandstones originate from the Northwest-German basin. The Wilkenson (e.g. Duda and Renner, 2013) and Berea sandstones (e.g. Christensen and Wang, 1985; Sayers et al., 1990; Woodside and Messmer, 1961; Tao et al., 1995; Prasad and Manghnani, 1997; Pagoulatos and Sondergeld, 2004; Mavko and Vanorio, 2010; Lin et al., 2011) originate from American quarries and are rock samples from the same blocks as the ones investigated respectively by Duda and Renner (2013) for the Wilkenson and by Riviere et al. (2016) for the Berea sandstone, respectively. The two rocks proved isotropic and homogeneous at the sample scale. From the dependence of their elastic properties on effective pressure, the Bentheimer, Wilkenson and Berea sandstones were shown to have many microcracks (e.g. Pimienta et al., 2017).

Scanning electron microscopy (SEM) imaging of thin-sections (Fig. 1), shows that the sandstone samples vary in porosity and grain size: greater than 100 μm for Bentheimer, Berea and Wilkenson sandstones, and less for all other samples.

Based on optical inspection, we consider almost all samples as homogeneous at the sample scale. Only the Anröchter Grün sandstone comprises millimetre-to-centimetre sized lenses of clay minerals. These visible lenses were avoided in our study. Thus, we also assume this rock sample as homogeneous at the sample scale (Fig. 1a). Moreover, none of our rock samples showed any layering nor did we observe any significant anisotropy in their physical properties.

2.2. Measuring methods

Most samples were machined to cylinders of about 50 mm diameter and lengths ranging from 50 mm to 100 mm. For calculating their volumes, we measured the dimensions with an accuracy of about 0.01 mm using a calliper gauge. We weighed the dry and water-saturated samples to assess the porosities, which confirmed the results obtained by Archimedes' method. Their thermal properties and P-wave velocities were measured using two bench-top devices explained in the following.

2.2.1. Thermal conductivity and diffusivity

Thermal conductivity (λ) and thermal diffusivity (κ) characterize how well a material conducts heat and how fast temperature diffuses in it, respectively. Density (ρ) and specific heat capacity (c_p) link these two thermal properties:

$$\kappa = \frac{\lambda}{\rho c_p}. \tag{1}$$

We measured λ and κ on dry and water-saturated samples using the combined mode of the optical scanning apparatus, which Popov et al. (2003) showed to be fast and accurate (about 5% error) in common rocks. With this method, the samples must be placed on the scanner between two reference samples (Fig. 2). A measuring module moves below the sample with constant velocity. It consists of (i) a" cold" infrared sensor measuring the initial sample temperature; (ii) an infrared heat source; and (iii) two "hot" infrared sensors measuring the sample temperature after heating, one in line with the source and the other slightly aside. λ is obtained by comparing the temperatures before and after heating and κ by comparing the two final "hot" temperatures (Fig. 2c).

Here, we do not provide all details of the method already explained, e.g. in Popov et al. (2016). However, the measuring conditions and regions probed by the method are of interest for the data interpretation. We acquired data under ambient conditions at a 5 mm scanning interval along the scanning line (Fig. 2c). We expect each of these measurements samples to probe an area of about 5 mm in diameter. The overall measurements probe the rock sample only to a limited depth (Fig. 3a) that varies with the thermal diffusivity of the sample and with scanning velocity and heater-sensor separation. Typical values reported by Popov

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