Journal of Applied Geophysics 140 (2017) 135–144

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Determining the relationship of thermal conductivity and compressional wave velocity of common rock types as a basis for reservoir characterization

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A R T I C L E   I N F O

Article history:
Received 7 August 2016
Received in revised form 31 March 2017
Accepted 1 April 2017
Available online 6 April 2017

Keywords:
Thermal conductivity prediction
Compressional wave velocity
Porosity
Saturation

A B S T R A C T

A comprehensive dataset detailing thermal conductivity and acoustic (compressional) wave velocity of 1430 oven-dry rock samples from clastic sedimentary (sandstone, arkose, greywacke), carbonatic (limestone, marl, dolomite, marble, coquina), plutonic (gabbro, gabbrodiorite, diorite, granodiorite, granite) and volcanic (basalt, andesite, rhyolite) rock types is presented. Correlation of thermal conductivity, compressional wave velocity and porosity are discussed in detail for each tested rock type. The study confirms that thermal conductivity of dry rocks can be predicted from acoustic velocity for porous rock types such as volcanites and sandstones, while non- and low-porous rocks show no to minor trends. With a prediction accuracy ± 0.5 W m^{-1} K^{-1} and a confidence of >80% for sediments and mafic volcanites the calculated data is far more comprehensive than data collected from literature, and is likely accurate enough for most first exploration approaches or geoscientific models before detailed site-scale investigation or modelling is conducted.

To investigate the effect of water saturation on thermal conductivity and compressional wave velocity 118 sedimentary samples (arkose and fine-, medium- and coarse sandstones) were saturated in de-aired water and the heat conduction and acoustic velocity were remeasured. The obtained data shows that both thermal conductivity and compressional wave velocity of saturated samples markedly increase in contrast to dry samples. The extent of the thermal conductivity and compressional wave velocity gain is mainly controlled by porosity. Thermal conductivity of saturated samples increases twice as much for higher porous samples than for low porous fine and medium sandstones. In contrast, the gain of compressional wave velocity of saturated sandstones decreases with increasing porosity.

1. Introduction

Thermal conductivity characterizes the heat transfer capabilities of materials as a result of a temperature gradient. It is a key property for various geoscientific applications such as geothermal modelling, sedimentary and basin studies, but also for geotechnical and construction applications. The heat transfer through a rock formation is typically realized through conduction and convection. Conduction (Fourier's law) dominates in dense, low-porous and impermeable rock types such as most plutonic and metamorphic rocks, but also in low permeable to impermeable sediments such as mudstones, dense carbonates or highly compacted sandstones. Under in-situ conditions convective heat transport dominates in permeable rock formations such as porous sediments or highly fractured or karstified rocks, where fluids can circulate through the interconnected pores, fractures and cavities.

Individual rock types typically exhibit a great variability of thermal conductivity due to heterogeneous mineral composition, variable textures and different porosity (Schön, 2015). Collections of thermal data of rocks (e.g. Bär et al., 2015; Cermak and Rybach, 1982; Clark, 1966; Clauser and Huenges, 1995) show the variability of rock thermal conductivities (Fig. 1). Most rock types typically exhibit a thermal conductivity range that spans over 3 to 4 W m^{-1} K^{-1}.

The correlation of thermal conductivity of rocks and other parameters or properties such as mineral composition, density and porosity, and fluid saturation has been investigated by numerous studies (Brigaud and Vasseur, 1989; Robertson, 1979; Schön, 2015; Somerton, 1958, 1992; Zimmerman, 1989). These studies have shown that the thermal conductivity of rocks is primarily controlled by mineral composition and porosity. In non- to very low-porous rocks, such as plutonic and metamorphic rocks, thermal conductivity is mainly controlled by the mineral composition and texture. In porous rocks, such as most sediments and extrusive rocks, thermal conductivity is primarily controlled by the porosity and structure of the pore space, which in turn primarily

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http://dx.doi.org/10.1016/j.jappgeo.2017.04.002

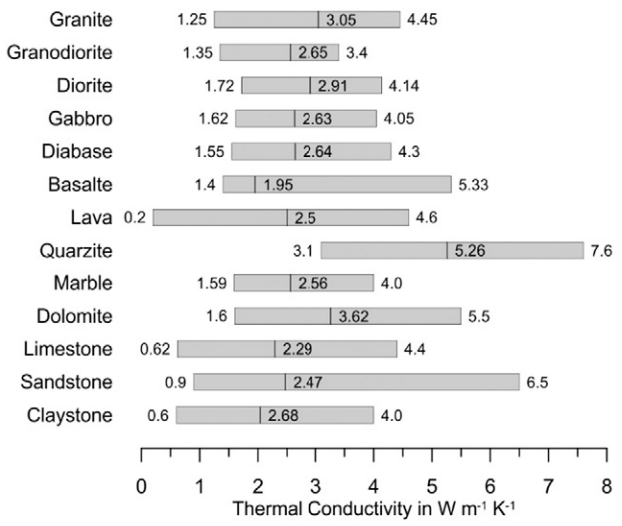

Fig. 1. Thermal conductivity ranges of common rocks.
After Cermak and Rybach, 1982.

depend on grain size distribution and sorting, and secondarily by mineral composition and cement type.

However, as the range of reported values is commonly quite large and do not reflect the local geological circumstances, the validity of literature values for a specific problem is often considered questionable (e.g. Fuchs and Balling, 2016a, 2016b; Schintgen et al., 2015). To obtain reliable thermal conductivity values it is essential to conduct large numbers of measurements that take the lithological and structural variability of the local strata into consideration.

1.1. Thermal conductivity measurement methods

Common direct measurement methods in laboratory are the divided bar method (Bullard, 1939; Sass et al., 1971), the line source method (Jaeger, 1958, and recent developments of this method e.g. Abid et al., 2014; Hammerschmidt and Meier, 2006), the laser flash method (Parker et al., 1961), and the optical scanning method (Popov et al., 1999). Unfortunately, laboratory measurements are often constrained by sample accessibility. In deep boreholes thermal conductivity can be measured by a range of downhole tools (e.g. Beck et al., 1971; Burkhardt et al., 1995; Hyndman et al., 1979; Kuriyagawa et al., 1983), but these methods typically work discontinuously and are uneconomic. In shallow boreholes the thermal response test (e.g. Gehlin, 2002) has emerged to a common tool. Deeper boreholes can be investigated directly applying the optical frequency domain reflectometry method (Lehr and Sass, 2014). Unconsolidated rocks need to be measured with a changeable water content and under increasing or decreasing compaction pressure (Sass and Stegner, 2012).

Consequently, indirect methods to determine thermal conductivity of rocks from other rock properties such as density, porosity, and mineral composition have been explored in many studies (e.g. Fuchs et al., 2013; Goutorbe et al., 2006; Gross and Combs, 1976; Hartmann et al., 2005). An extensive literature compilation of various empirical relationships and proposed equations for the indirect determination of the thermal conductivity of a rock formation is given by Fuchs et al. (2013), and an overview of most common model concepts is given by Schön (2015). In conclusion, these regression-based empirical equations are typically limited to the specific rocks on which they were established for and are therefore not universally applicable.

1.2. Thermal conductivity and acoustic velocity

Another indirect method to predict thermal conductivity is its relationship to acoustic (compressional) wave velocity. Applying acoustic velocity as a proxy to predict thermal conductivity of rocks or entire rock formations has the advantage of relying on a standard method that has been successfully applied in reservoir and basin exploration for decades, and can be applied in the laboratory as well as in boreholes and large-scale field surveys. The relationship between thermal conductivity and acoustic velocity is based on the phonon conduction theory, that assumes thermal energy transfer occurring through the propagation of acoustic wave packets (phonons) along a thermal gradient (Horai and Simmons, 1969; Pribnow et al., 1993; Williams and Anderson, 1990). Both thermal conductivity and acoustic velocity are primarily controlled by the heat and acoustic wave conduction of the rock-forming minerals and the type and amount of cementation, which connects the individual grains. In contrast, "defects" such as pores, microfractures and associated grain-to-grain boundary effects interfere with the phonon flow through the rock. Consequently, both thermal conductivity and acoustic velocity decrease with increasing porosity (hence increase with bulk density).

By contrast, the mineral composition can influence thermal conductivity and acoustic velocity in opposing directions. Generally, mafic minerals exhibit higher densities than felsic minerals, hence both rock properties should increase for mafic rocks. However, quartz exhibits low density but high thermal conductivity as compared to other rock-forming mafic and felsic minerals (mostly feldspar and other silicate minerals). As quartz is the main constituent of felsic rock types, its relatively high thermal conductivity causes an increase of thermal conductivity from basic/mafic (e.g. gabbro, basalt) to acid/felsic (e.g. granite, rhyolite) rock types, while acoustic wave velocity decreases due to the lower density of felsic rocks as compared to mafic rocks (Schön, 2015).

1.3. Existing data

Published studies that substantiate or disprove the applicability of predicting thermal conductivity from acoustic velocity are rare and show inconsistent results. Esteban et al. (2015) predicted the thermal conductivity of 179 dry and wet sandstones from the Perth basin (Australia) and Soultz-sous-Forêts (France) from acoustic velocity, porosity and simplified mineralogy using a model from Pimienta et al. (2014), and reported a good match with measured thermal conductivity data from the same samples. Kukkonen and Peltoniemi (1998) measured petro-physical data including compressional wave velocity and thermal conductivity of more than 700 crystalline core samples from Finland, but found no significant correlation. Popov et al. (2003) published data from more than 800 core samples of sedimentary rocks from different Russian hydrocarbon deposits and impact rocks from the well "Nördlingen 1973" drilled in the Ries impact structure (Germany), and concluded that correlations exist between thermal conductivity and acoustic velocity, but strongly depend on the local conditions. A study by Hartmann et al. (2005) investigated the correlation of thermal conductivity and compressional wave velocity for shaly sandstones and marls, and suggested that good correlations exist, but strongly depend on the local conditions and diagenesis of the rock. Gegenhuber and Schön (2012) measured both thermal conductivity and compressional wave velocity on a total of 35 samples consisting of mainly granite, basalt and sandstone and concluded that good correlations exist. A good correlation of both properties was also confirmed by Özkahraman et al. (2004) who tested a small sample set of limestones and andesite.

Large quantities of laboratory measurements of thermal conductivity and acoustic velocity are typically done on dry samples at ambient conditions. The standardized measurement conditions allow direct comparison of the different rock types, but do not reflect the in-situ conditions at depth. Porosity commonly decreases with depth due to increasing overburden stress, which in turn facilitates improved heat and acoustic wave conduction by up to 30% (e.g. Birch, 1960; Clauser and Huenges, 1995; Horai and Susaki, 1989; Schön, 2015; Walsh and Decker, 1966). In contrast, elevated temperatures at depth can cause