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Thermal Conductivity Log out of Correlations for Carbonates from Austria

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SUMMARY

Thermal conductivity is a cruicial property of geothermal and other applications like tunneling or geological/thermal modelling. It is hardly possible to measure thermal conductivity directly in the borehole, therefore most data available are laboratory data. Therefore the correlation between thermal conductivity and other petrophysical parameters (here: electrical resistivity) are used for a derivation of a "thermal conductivity" log for carbonates. Thermal conductivity is calculated using an inclusions model, in contrast to the electrial resistivity where the Archie equation is used. Out of the calculations two petrographic coded equations resulted. Different pore spaces and the petrographic code is demonstrated using different values for m (empirical Archie exponent) depending on the rock type. The derived euaqtions give us the possibility to derive a "thermal conductivity" log out of a resistivity log. Two examples show for different carbonates (petrographic code) that the equations can be easily applied for thermal conductivity estimation, when logs of electrical rock resistivity and resistivity of the water are present. The mean log-derived thermal conductivity values from the logs fit well to the measured data at outcrop samples of the same rock type.

Introduction

Thermal conductivity is a crucial property for geothermal projects as well as tunnelling or geological modelling. It is also important for hydrocarbon maturation processes and thermal modelling. Available data are mainly from laboratory measurements because it is almost impossible to determine thermal conductivity in the borehole.
In the last few years thermal conductivity become more and more important. Fuchs (2013) published in his PhD thesis a combination of three papers concerning thermal conductivity measurements in the laboratory, different mixing rules and a well-log based prediction of thermal conductivity. Sundberg et al. (2009) published the general relationship between thermal conductivity and density for igneous rocks. Whereas Hartmann et al. (2005) presented correlations between thermal conductivity and porosity, compressional wave velocity and density for shaly sandstone and marl. The derivation of thermal conductivity from p-wave velocity for building rock types was published by Oezkahram et al. (2004). Popov et al. (2003) divided a collection of data into six subcategories, from different silt and sandstone, to limestone and granite as well as gneiss and amphibolite samples. Correlations display again the general trends for thermal conductivity and porosity, electrical resistivity and permeability. Depending on the rock type, regression curves fit well to the data for porosity and electrical resistivity.
First calculations and results for magmatic and metamorphic rocks using correlations between thermal conductivity and compressional wave velocity showed good results (Gegenhuber and Schön, 2011). For carbonates the used models and resulting correlations did not work. Therefore the electrical resistivity was considered, where the correlations are described using Archies's equation for the resistivity and an inclusions model for the thermal conductivity. The derived equations for the relationship between electrical resistivity and thermal conductivity were further applied on borehole data, to calculate a thermal conductivity log.

Materials and Methods

For our calculations different carbonates with low porosities from Austria are used. The "Dachstein"-limestone is from a stone pit in Ebensee (Upper Austria). The dolomite samples are also from pits from lower Styria, whereas the "Haupt"-dolomite samples are from a pit in Gaaden/Mödling (Lower Austria) and the "Wetterstein"-dolomite samples are from a stone pit in Rohrbach (Upper Austria). All samples from the stone pits were fresh and had no alteration marks.
Thermal conductivity and electrical resistivity were determined in the laboratory. Thermal conductivity measurements were carried out with the thermal conductivity meter TK04 (from TeKa, Berlin). This instrument is a non-steady state (transient) method (line source). The half-space-line source and the sample are fixed by a contact pressure of 15 bars (=1.5E6 Pa). Between probe and sample a contact agent (here: Nivea cream) was used, to establish an optimal thermal contact. The temperature is measured as a function of time at the midpoint of the needle with a thermistor. Thermal conductivity is calculated directly from the heating curve. The reproducibility is 1.5 % in relation to conductivity. Samples are measured dry and saturated. The difference is in the range of the reproducibility (because of the low porosity) (Gegenhuber, 2013).
The important factors of electrical measurements are the pores and fractures, which are filled with water, because these act as conductors, whereas minerals (except of ores) act as isolators. The correlation between water saturation, porosity, water resistivity and rock resistivity is described by Archie's equations (Archie, 1942). Specific electrical resistivity is measured at low frequencies (8.5 Hz). Temperature and conductivity of the water are measured with a conductivity meter (Type: LF 325 from WTW, Germany). For the measurements on saturated samples, a 4-point-light instrument (LGM Lippmann) and a 4-electrode configuration were used. Samples are saturated with NaCl solution (20 g NaCl with 1 l distilled water) under vacuum for 12 hours. This salinity results in a water resistivity of 0.30 Ohmm (22.7°C). The cylindrical 1-inch cores get wrapped with Teflon tape so that no parallel bypass current can flow outside the sample and the samples cannot loose water and dry out. Electrode A, B send an alternating current into the sample; the voltage is measured between the two copper wire electrodes M, N. All measurements were repeated three times for verification and calculating the mean value and were carried out at room temperature.

Model calculations

For the correlations a forward calculation is used. The two main factors for thermal conductivity are the mineral composition and the porosity. These are described using an inclusions model (Clausius-Mossotti, in Berryman, 1995). The diversity of pore geometry is represented by the aspect ratio (α). Used is an aspect ratio of α=0.01 for all calculations, which characterize penny shaped cracks (Mavko et al., 2011).
For the correlations thermal conductivity for the two minerals dolomite (7.0 $Wm^{-1}K^{-1}$), calcite (4.0 $Wm^{-1}K^{-1}$) (Schön, 2011), and the pore content (air=0.025 $Wm^{-1}K^{-1}$) with the sample porosity are used (Gegenhuber, 2013).
For the electrical resistivity the Archie equation (equ. 1) is used for the calculations.

$$R_0=R_w*F=R_w/\phi^m \quad (1)$$

Archie's equation (equ. 1, Archie, 1942) gives the link between specific rock resistivity (R_0), porosity ϕ and pore water resistivity (R_w), with which the sample is saturated. It is only valid for clay free and fully saturated samples. M is the empirical Archie exponent, which covers the different types of pores. The diversity of pore geometry for different rock types (petrographic code) is represented using different exponents m to calculate the formation factor. Figure 1 shows that limestone can be described with m=1.8 and the dolomite using m=1.6. This can be explained due to the different pore geometry. Generally m=1.5 displays a mixture of fractured and interparticle porosity whereas m=2 is characteristic for sandstone and carbonate samples with interparticle porosity.

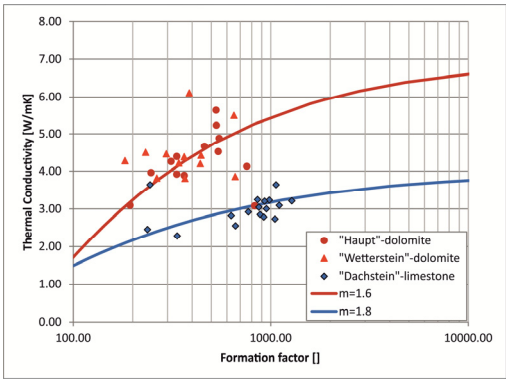

Figure 1 *Thermal conductivity versus formation factor, points show measured data, lines are calculated with the inclusions model (thermal conductivity) and Archie equation (formation factor); red: dolomite, blue: limestone.*

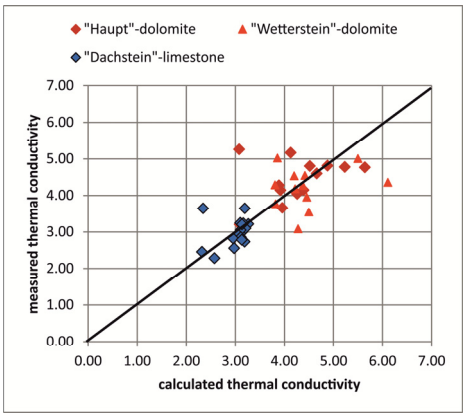

Figure 2 *Thermal conductivity calculated versus thermal conductivity measured [$Wm^{-1}K^{-1}$], line shows optimal fit.*

Figure 2 shows the cross plot measured thermal conductivity versus calculated thermal conductivity from resistivity measurements. The developed equations (Table 2) were therefore applied on laboratory resistivity measurements.
For an application the calculated curves in Figure 1 were described in good approximation by polynomial regression (Table 1). With these equations, the calculation of a "thermal conductivity" log from a resistivity log (with additionally known water resistivity) becomes possible.

Rock type	
Dolomite	$\lambda=11.10*1/F-56.68*1/F^{0.5}+7.21$
Limestone	$\lambda=32.291/F-28.65*1/F^{0.5}+4.04$

Table 1 *Correlation equations for dolomite and limestone, λ=thermal conductivity [$Wm^{-1}K^{-1}$].*

Application on log data

For the application two wells in Austria were selected. No cores were available from the boreholes directly, but the selected lithologies correspond to samples from outcrops which were available and measured in the laboratory.
In the first well "Dachstein"-limestone is present. Displayed in Figure 3a are the density, resistivity and the calculated thermal conductivity log. The mean value of the measured thermal conductivity of the (dense) "Dachstein"-limestone in the laboratory is 2.98 $Wm^{-1}K^{-1}$. The mean value between 1200 and 1400 m of the calculated thermal conductivity log is 2.77 $Wm^{-1}K^{-1}$ and match therefore really good.

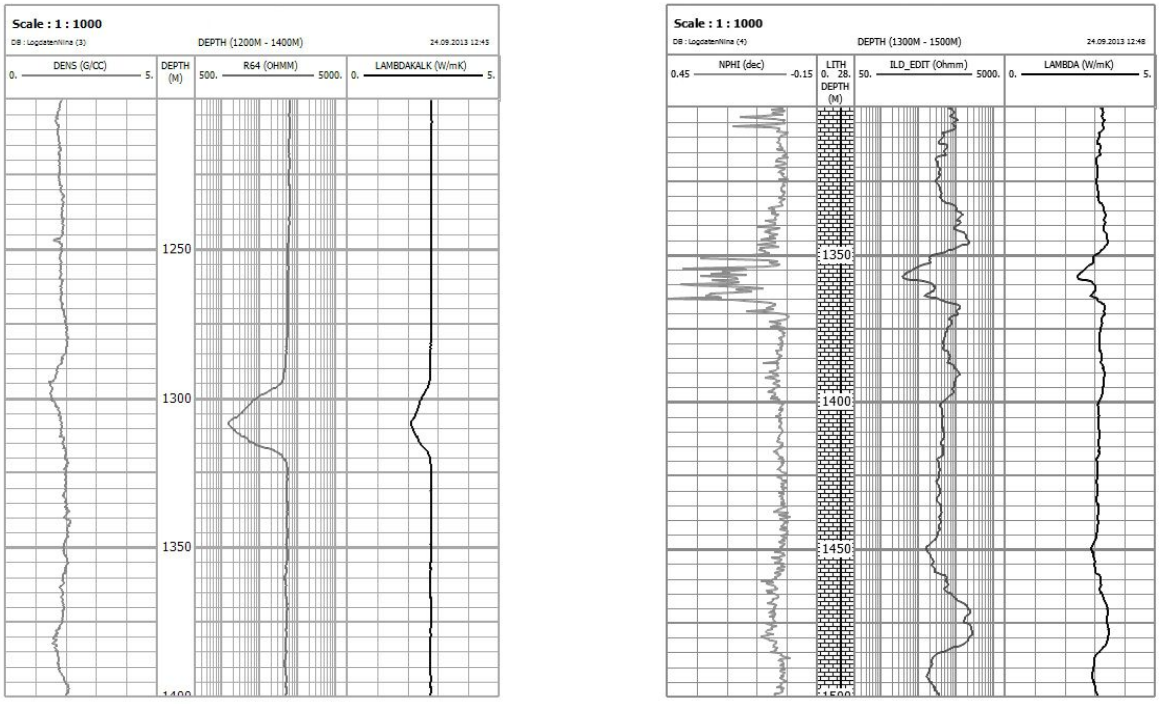

Figure 3a and b *Log example, 3a (left): "Dachstein"-limestone, track 1: density log, track 2: resistivity log and track 3: calculated thermal conductivity log, mean value: 2.77 $Wm^{-1}K^{-1}$; 3b (right): "Schoeckel"-limestone, track 1: porosity log, track 2: resistivity log, track 3: calculated thermal conductivity log, mean value: 3.13 $Wm^{-1}K^{-1}$.*

The second well (Figure 3b) shows the "Schoeckel"-limestone in the depth between 1200 and 1600 m. Here also laboratory data (only thermal conductivity at the moment) of outcrop samples are available. The mean value of these values is 3.82 $Wm^{-1}K^{-1}$. The mean value of the calculated thermal conductivity log between 1200 and 1500m is 3.13 $Wm^{-1}K^{-1}$.

Conclusion

Thermal conductivity is one crucial parameter for geothermal research and other applications. A direct measurement in most cases is only possible at rock samples in the laboratory. As in other situations in applied geophysics therefore an "indirect" determination – a derivation from other physical properties using correlations – would be a practical solution. Based on log measurements for example electrical resistivity and elastic wave velocity are such preferred measurements, which are standard measurements.
Two factors with different influence control the relationship between thermal conductivity and electrical properties: The mineral composition and fractures, pores and other "defects". Therefore, a model concept must represent these two factors – a so called "petrographic coded model". The developed equations fit well. The derived equations – transferred to borehole data - are a powerful tool especially for geothermal projects. They give the possibility to predict thermal conductivity out of resistivity logs depending on the rock type for carbonates.
The two examples showed for different carbonates (petrographic code) that the equations can be easily applied for thermal conductivity estimation, when logs of electrical rock resistivity and resistivity of the water are present. The depth influences can be seen also in the thermal conductivity log. Fracturing lowers for example resistivity as well as thermal conductivity. The mean log-derived thermal conductivity values from the logs fit well to the measured data at outcrop samples of the same rock type.
Accuracy, resolution and representative rock volume of direct sample measurement and "log derived" thermal conductivity are different (this results from the different measuring principles and techniques), but the log-derived conductivity gives a good approximation and has the advantage of a continuous profile.

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