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Petrographic Coded Model Correlations to Derive a Thermal Conductivity-Log

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ABSTRACT

Thermal conductivity is one of key properties of some applications, such as petroleum engineering, geothermal engineering, civil engineering and hydro-geological studies. Due to difficult measurements of the thermal conductivity in boreholes, in most cases only laboratory values are available. Therefore the knowledge of correlations between the thermal conductivity with other petrophysical properties measurable in wells or from the surface (seismic wave velocity, electrical resistivity) could deliver indirectly thermal conductivity. Our approach was to correlate thermal conductivity with compressional wave velocity for magmatic rocks and sandstone as well as with electrical resistivity for carbonates. Compressional wave velocity, thermal conductivity, electrical resistivity and porosity were therefore determined in our laboratory at different rock types. Two models were applied in order to formulate the basic structure of a correlation between compressional wave velocity and thermal conductivity: a defect and an inclusions model. The solid mineral composition values were taken from the literature. The types of rock were divided into: granite and gneiss, gneiss respectively granite with higher content of quartz, basalt/gabbro/diorite and sandstone. Groups indicated a petrographic code as a property, which controls the correlation. Both models gave a good fit to measured data. With the derived equations, calculation of thermal conductivity log out of a sonic log was possible. Next step was to use the inclusions model and the Archie equation for the calculation of thermal conductivity and electrical resistivity for carbonates, where the other correlations did not work. The derived equations for dolomite and limestone were further applied on resistivity logs, which worked well. To summarize, it can be said that the developed petrographic coded correlations out of the laboratory values worked well for the selected rocks. They showed the two important factors that influence the thermal conductivity: the effect of mineral composition and cracks/fractures/pores. The prediction of the thermal conductivity log out of sonic and resistivity log worked well.

1. INTRODUCTION

Thermal conductivity is one of the key properties in geothermal studies, geological and geothermal modelling, tunneling and mining. Due to difficult determinations of thermal conductivity in boreholes, most data available are laboratory data. Measuring of thermal conductivity is possible in a borehole but time consuming and it is difficult to predict a good sensor contact with wall of borehole (Burkhardt et al., 1990). Thus it would be good to have a correlation of the thermal conductivity with other petrophysical properties that can be obtained with borehole or field measurements. Thermal conductivity is important for valuation of low permeability in geothermal systems where large convection is insignificant. In this paper, correlations between thermal conductivity and compressional wave velocity as well as electrical resistivity and resulting equations are presented for a derivation of thermal conductivity. Sonic and electrical resistivity logs are standard data and can be measured easily.

Many previous studies aimed to express relationships with different petrophysical properties. Rybach and Buntebarth (1982) did regression analysis for relationships of thermal conductivity with density, seismic velocity, heat generation and mineralogical constituents. The data (granite, granodiorite, diorite, gabbro, amphibolite, peridoite, tonalite, hornblendite) reflect the general trends but data scatter and no further calculations have been completed.

Relationships of thermal conductivity with other petrophysical properties like density, magnetic susceptibility or compressional wave velocity by using 2705 core samples of plutonic rocks (granite, tonalite,..), dykes (diabase, kimberlite,..), volcanic rocks (lava, tuffite,..), sedimentary rocks, metamorphic rocks (schist, gneiss, migmatite,…) and altered rocks from Finland were published by Kukkonen and Peltoniemi (1998). They sum up that there was no general trend for correlations between thermal conductivity and other petrophysical properties, while the data scattered.

In his PhD thesis Fuchs (2013) described the well-log based determination of rock thermal conductivity in the North German Basin. The main rock types were sandstone and siltstone. In the thesis three published papers were combined, where the measurements on samples in the laboratory, different mixing rules for thermal conductivity calculation and a well-log based prediction of thermal conductivity were discussed.

An article by Popov et al. (2003) gave an overview over some correlations for various rock types. They divided the rocks in 6 collections from different silt- sandstones, to limestone and cores from the scientific well “Nördlingen 1973” with granites, gneiss and amphibolite. The correlations reflected known trends between thermal conductivity and porosity, electrical resistivity and permeability (thermal conductivity decreases with increase in porosity, electrical resistivity and permeability). Furthermore, they put regression lines to these correlations, which fit well for the resistivity and porosity, depending on the rock types.

The general relationship between thermal conductivity and density for igneous rocks was published by Sundberg et al. (2009). They additionally used density logs for the correlation. Hartmann et al. (2005) demonstrated the correlation of thermal conductivity with porosity, compressional wave velocity and density for shaly sandstones and marls, not only for laboratory measurements but also for well log data. They also noted that those correlations were only valid for local conditions. Moreover Oezkahraman et al. (2004) described derivation of thermal conductivity from p-wave velocity for building rock types.

The thermal regime of the Eastern Alps due to inversion analyses was presented by Vosteen et al., (2003). They carried out petrophysical measurements and did inversion modelling. Vosteen and Schellschmidt (2003) published in their paper dependence of thermal conductivity on thermal capacity concerning pressure and temperature. They cited that the influence of temperature was different for crystalline and sedimentary rocks and presented a general equation of temperature dependence on thermal conductivity for Eastern Alpine rocks. Further work was presented by Abdulagatova et al. (2009) and Abdulagatov et al. (2006), who also discussed effects of temperature and pressure on thermal conductivity. Abdulagatov et al. (2006) used five dry rocks (sandstone, limestone, amphibolite, granulite and pyroxene-granulite) and measured thermal conductivity in different pressure and temperature ranges. Additionally, different effects of structure, mineralogical composition and porosity were discussed. In contrast Abdulagatova et al. (2009) used dry sandstone samples for their paper.

The prediction of thermal conductivity through physico-mechanical properties was presented by Singh et al. (2007). They tested different models on 15 data sets and predicted thermal conductivity using p-wave velocity, porosity, bulk density and uniaxial compressive strength. A similar topic was described by Yasar et al. (2008), which used limestone, dolomite, marble, sandstone, siltstone and basalt from parts of Turkey to derive thermal conductivity from p-wave velocity, porosity and uniaxial compressive strength.

Summarizing there has been no general model concept for a practical application upon main rock types and for derivation of thermal properties from other geophysical parameters. We aimed to find a correlation using not only linear regressions but two simple models: a defect model and an inclusions model. Both demonstrated dominant influences: mineral composition and cracks/fractures, which were proved as reliable and descriptive tools for magmatic rocks. Petrographic-coded correlations between thermal conductivity and compressional wave velocity/electrical resistivity were obtained.

For magmatic and metamorphic rocks as well as sandstone samples, the correlation between thermal conductivity and compressional wave velocity was applied while the correlation with electrical resistivity was used for carbonates but did not work. The important point here is that the samples did not include clay. With these correlations and lithology information thermal conductivity can be calculated from sonic/acoustic and resistivity logs. Furthermore these “thermal conductivity logs” can be used as input for geothermal applications, tunnel projects or hydrogeological studies.

2. METHOD

The following subsections will describe the used rock types and additionally the determination of thermal conductivity, compressional wave velocity and electrical resistivity in a laboratory experiment. All data presented were measured under dry conditions at room temperature (except of the resistivity, where saturated samples were required).

2.1 Rock types

On the one hand we used magmatic and metamorphic rock types and sandstone samples in order to evaluate a correlation between thermal conductivity and compressional wave velocity. For carbonates a correlation between thermal conductivity and electrical resistivity was needed due to a bad correlation with the compressional wave velocity.

Different types of rock were selected from the rock sample collection “Lithothek” located at the Technical University of Graz. In order to derive relationships and correlations for different rock types of different geological units of Austria, the samples were selected from among:

- sedimentary rocks (clastic sediments)
- magmatic and metamorphic rocks (granite, gneiss and basalt).

Four or five samples of each type of rocks (granites, sandstones, basalts, and diorites) were used for the first systematic measurements of physical properties. Because of their polished surface, the results from the thermal conductivity measurement were really good without any preparation before the measurement. The shape of the samples and conservation limited the possibility for the measurements. There was no feasibility to get the resistivity or the porosity, because saturated samples would be needed and we were not allowed to saturate them.

To obtain more data for the correlation between compressional wave velocity and thermal conductivity, further granites and basalts were obtained from fields. The granites were from upper and lower Austria. These had different grain size and density. The basalt was from Klöch in Styria. Two cretaceous sandstone samples from Pirna in Germany were measured. Additionally, laboratory data from two geothermal projects (Vienna basin and Tauern window (granites and gneiss samples)) in Austria were used and granites from India and sandstone from Paraguay. The last two samples are data from two projects where petrophysical measurements were carried out in our laboratory.

Different carbonates (dolomite and limestone) were selected in Austria for the correlation between thermal conductivity and electrical resistivity. Used samples are “Wetterstein”-dolomite, “Haupt”-dolomite and “Dachstein”-limestone. “Wetterstein”-dolomite is part of the middle Triassic and the lower part of the upper Triassic section. In contrast, “Haupt”-dolomite and “Dachstein”-dolomite are upper Triassic units of the Northern Calcareous Alps.

2.2 Laboratory data

2.2.1. Thermal conductivity

A transient method was used to measure the thermal conductivity (TK04, TeKa, Berlin, Germany). This method determines a value, which represents the thermal conductivity λ in a plane perpendicular to a line source. A half-space line-source (HLQ) (needle is encased in a cylinder) was pressed onto the sample. With a probe plane of 10 x 10 cm and a needle length of 7 cm (Plexiglas cylinder: diameter: 9 cm), boundary effects were negligible. The HLQ and the sample were set at a contact pressure of 15 bar. In order to establish an optimal heat flow between the probe and the sample a heat transfer agent (Nivea) was applied.

During the analysis, the line-source was heated by a defined heating power (3 Wm^{-1}) and the temperature was measured at the midpoint of the needle. The heating period was 80 seconds and the process was repeated 99 times to detect the maximum temperature. The result in the heating/cooling cycle was recorded and analysed. Thermal conductivity was calculated directly from the heating curve (Davis et al. 2007). For each measurement the needle was rotated clock-wise in 45° steps. This would have been recognized as an anisotropic effect. The reproducibility of the value of conductivity λ was ±1.5 %. For this study at least two measurements for each repeated five times were carried out. A weighted average was calculated and the standard deviation of the results was determined between 0.01 and 0.2 $Wm^{-1}K^{-1}$.

2.2.2. Compressional wave velocity

The compressional wave velocity was determined with an ultrasonic device on core samples (diameter = 1 inch =2.54 cm). The samples were set between a transmitter and a receiver with a contact agent (ultrasonic gel) at a pressure of 5 bar. Both transducers were piezoceramic systems (Type: S12, HB0.8-3 vertical probe, Karl Deutsch, Germany) designed for compressional wave measurement. A singular impulse (frequency = 10 kHz, amplitude = 5 V) was sent to the transducer and results in a mechanical pulse transmitting the sample. The arriving signal was visualized on a computer screen with a storage oscilloscope.

A program, which was developed at our chair with MATLAB, detected the first arrival and calculated the velocity from the digitally stored signal. At the start of each new measurement cycle, the dead time (delay time between electrical impulse and mechanical pulse) was determined in all measurements. The reproducibility is about 1 % of the compressional wave velocity. Three measurements were taken for each sample and the mean value was calculated.

2.2.3. Electrical resistivity

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). The Archie equation is only valid for clean, clay free samples where water is only conductive component. Specific electrical resistivity was measured at low frequencies (8.5 Hz). The temperature and the conductivity of water were 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 were saturated with NaCl solution (20 g NaCl with 1 l distilled water) under vacuum for 12 hours. This salinity resulted in a water resistivity of 0.30 Ohmm (22.7°C). The cylindrical 1-inch cores were wrapped with Teflon tape so that no parallel bypass current can flow outside the sample and the samples cannot loose water nor dry out. Electrode A and B sent an alternating current into the sample; the voltage was measured between two copper wire electrodes M and N. For the contact of sample and copper wire, small, thin and wet sponges were used. All measurements were repeated three times for verification and calculation of the mean value and were carried out at room temperature.

3. MODEL CALCULATIONS

Models used in this study implemented simplifications mainly of internal geometry of rocks (structure, texture). Experimental investigations showed that thermal conductivity was controlled mainly by mineral composition, porosity and/or fracturing. The magnitude of thermal conductivity is dominated by the solid mineral components (particularly quartz with highest thermal conductivity). Among the "geophysical" properties, seismic velocity shows some similarities: Seismic velocity is also controlled mainly by mineral composition, porosity and/or fracturing. The magnitude of elastic wave velocities is dominated by solid mineral components as well. As a conclusion, models are used for the following derivations between thermal conductivity and compressional wave velocity/resistivity. It consists of two steps:

Step 1: Modelling of solid matrix properties (thermal conductivity, density, and elastic properties) of host material, which uses input data from the literature.

Step 2: Implementation of pores and fractures using different models.

3.1. Inclusion model

The idea behind inclusion models is a homogeneous solid material with isolated pores or cracks. The pores and cracks are modelled mostly as ellipsoidal inclusions described by the aspect ratio. The geometry of the inclusion can be varied by its size and aspect ratio. Size, aspect ratio and concentration (number) of inclusions give the porosity. The properties of solid host material can be varied depending on the material composition (mineral content). Berryman (1995) described various models for rock properties, such as dielectric properties and elastic constants. Earlier models were from e.g. Clausius-Mossotti (in Mavko et al. (2011)).

Budiansky and O'Connell (1976) derived with a self-consistent algorithm an equation for the elastic properties assuming a penny-shaped crack medium, which forms the basis for calculations of the inclusions model. Compressional modulus k_{sc} and shear modulus μ_{sc} result as:

$$k_{SC} = k_S * \left[1 - \frac{16}{9} * \frac{1-\nu^2_{SC}}{1-2*\nu_{SC}} * \varepsilon\right] \quad (1)$$

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$$\mu_{SC} = \mu_S * \left[1 - \frac{32}{45} * \frac{(1-\nu_{SC})*(5-\nu_{SC})}{2-\nu_{SC}} * \varepsilon\right] \quad (2)$$

where k_s is the compression modulus for the solid material, ν_{sc} is the Poisson's ratio and μ_s is the shear modulus for the solid material (Mavko et al., 2011). ε is a "crack density parameter" as follows:

$$\varepsilon = \frac{N}{V} * r^3) \quad (3)$$

where N is the number of cracks per unit volume (V) times. r is the crack radius,

The crack porosity is

$$\phi = \frac{4*\pi}{3} * r * \varepsilon \quad (4)$$

and results with the effective Poisson's ratio in:

$$\nu_{SC} \approx \nu_S * (1 - \frac{16}{9} * \varepsilon) \quad (5).$$

The equations (2), (4) and (5) present some remarkable characteristics:

- in equation (2) the second term in brackets describes an effect of inclusions on the elastic moduli of the rock
- this effect of the elastic moduli is controlled only by Poisson's ratio of the host material ν_s and the "crack density parameter" ε
- equation (4) shows after rearrangement that the crack density ε represents a combination of porosity φ and aspect ratio α

This explains a porosity and high aspect ratio can have the same effect as low porosity and low aspect ratio. Porosity alone is not sufficient to describe thermal and elastic (or more general-tensorial) properties of a rock.

In addition the density ρ needs to be calculated to get the compressional wave velocity (v_p):

$$\rho = (1 - \phi) * \rho_s + \phi * \rho_{air} \quad (6)$$

which results in

$$v_p = \left(\frac{\frac{3}{k_{sc}} + \frac{4}{\mu_{sc}}}{3*\rho}\right)^{1/2} \quad (7)$$

where ρ_s is the density of the matrix and ρ_{air} the density of the air.

The equations of Clausius-Mosotti (see Berrymann, 1995) can be used for calculation of thermal conductivity. This inclusions model is used for both types of correlations with compressional wave velocity and electrical resistivity.

$$\lambda_{CM} = \lambda_S * \frac{1-2*\phi*R^{mi}*(\lambda_S-\lambda_i)}{1+\phi*R^{mi}*(\lambda_S-\lambda_i)} \quad (8)$$

where

$$R^{mi} = \frac{1}{9} * \left(\frac{1}{L_{a,b,c}*\lambda_i + (1-L_{a,b,c})*\lambda_s}\right) \quad (9)$$

where λ_i is the thermal conductivity of the inclusions. λ_s is the thermal conductivity of the solid mineral composition. R^{mi} is a function of depolarization exponents L_a, L_b, L_c where the subscripts a,b,c refer to axis directions of the ellipsoid. Depolarization exponents are related to the aspect ratio. There are also values and approximations for some extreme shapes:

sphere L_a=L_b=L_c=1/3

needle L_c=0 (along needle long axis), L_a=L_b=1/2 (along needle short axes)

disk L_c=1 (along short axis), L_a=L_b=0 (along long axes).

3.2. Defect model

Our second approach is a defect model for a correlation between thermal conductivity and compressional wave velocity. The defect parameter in a solid matrix is characterized by its relative length D (Schoen, 2011).

As a first approximation and using only linear terms, decrease of parameters caused by defects of a dry rock (fractures, cracks) can be described as follows:

$$k_{rock} = k_s * (1 - D) \qquad \mu_{rock} = \mu_s * (1 - D) \qquad v_{p,rock} = v_{p,s} * \sqrt{1 - D} \quad \lambda_{rock} = \lambda_s * (1 - D) \quad (10)$$

where k_s, μ_s, $v_{p,s}$ and λ_s are the values for the compressional modulus, the shear modulus, the compressional wave velocity and the thermal conductivity of the solid matrix block, respectively. The relationship between thermal conductivity λ and elastic wave velocity v_p can be described by the following equation:

$$\lambda_{\mathrm{rock}} = v^2{}_{\mathrm{p,rock}} * \left(\frac{\lambda_s}{v^2{}_{\mathrm{p,s}}}\right) = v^2{}_{\mathrm{p,rock}} * A_s \quad (11)$$

The equation reflects the correlation between the thermal rock conductivity and the square of elastic wave velocity as a result of the defect influence. The rock type ("petrographic code") is expressed as the parameter A_s (solid matrix value), which is controlled only by mineral composition and properties measured at the same position as host material in case of inclusion models. A solid matrix value (A_s) needs to be determined or defined for calculations in the defect model, using the equations (10). The same input values as for the inclusions model were used.

3.3. Archie equation

Archie's law (Eq. (12)), for water saturated clean rocks gives a direct link between specific rock resistivity (R_0), porosity φ and pore water resistivity (R_w) as follows:

$$R_0 = R_w * F = R_w / \varphi^m \quad (12)$$

where m is the cementation exponent, which covers the different types of pores. With Archie's law for different values of m the electrical resistivity was modelled for the correlation between thermal conductivity and the resistivity for the carbonates.

4. RESULTS

The results from the inclusions model are displayed in figure 1. The four curves fitting the different rock types were calculated for different input values for the host material and different aspect ratios characterizing the inclusion shape. Input parameters for the different correlations are summarized in Table 1.

	k_s	μ_s	ρ_s	v_p	λ_s	α
	GPa	**Gpa**	**g/cm³**	**m/s**	**W/mK**	**[]**
Granite/Gneiss-lower quartz content	49	27.9	2.80	5550	3.5	0,20
Granite/Gneiss-higher quartz content	34	19.4	2.80	4622	4.0	0,20
Basalts/Gabbros	80	45.6	3.30	6532	3.0	0,25
Sandstones	7	3.99	2.65	4086	5.0	0,2

Table 1: Input data for the calculations of the solid host material for the inclusion model; k_s = bulk modulus, μ_s = shear modulus, ρ_s = density, v_p =compressional wave velocity, α = aspect ratio.

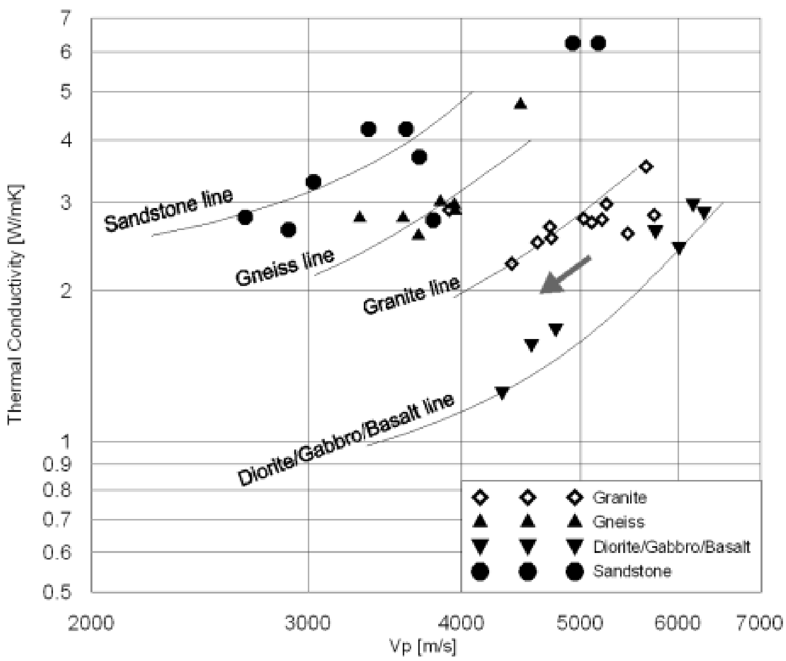

Figure 2: Calculated relationships between compressional wave velocity and thermal conductivity based on the inclusions model. The grey arrow indicates the increase in the porosity.

For the inclusions model, the fitting parameter is the aspect ratio. The best-fit aspect ratio α was 0.20 for granites and gneiss with higher and lower content of quartz. This represents fractures and pores with an axis ratio of 1:5. Basalt/diorite/gabbro obviously show not such a flat shape with the aspect ratio of 0.25 and the axis ratio of 1: 4. The aspect ratio of 0.2 for sandstones results in an axis ratio of 1:5.

Figure 2 presents the results calculated by the defect model in comparison with the measured data. For application of the defect model the data were divided in the same four types of rocks: basalt/diorite/gabbro, granite and gneiss (respectively granite and gneiss with higher content of quartz and sandstone). The defect model was plotted with a logarithmic scale. The fitting parameter is the value A_s, which is defined as: $\lambda_s/v^2_{p,s}$.

There was a high correlation between the experimental data and the calculated curves by the inclusions model except the sandstone with low content of quartz. Both models were controlled by the mineral composition and the fractures/pores. The inclusions model, which can demonstrate these two influences, has a factor controlling the aspect ratio. The correlation coefficients for the inclusions model showed around 0.9 for the sandstone and granite/gneiss with high content of quartz which, which means a good correlation of both properties (thermal conductivity and compressional wave velocity) between measured data and calculated values. The correlation coefficients for basalt/diorite/gabbro were 0.77 and 0.74, which demonstrate a moderate correlation between them. Only granite/gneiss with low content of quartz showed a moderate value of 0.63 for compressional wave velocity.

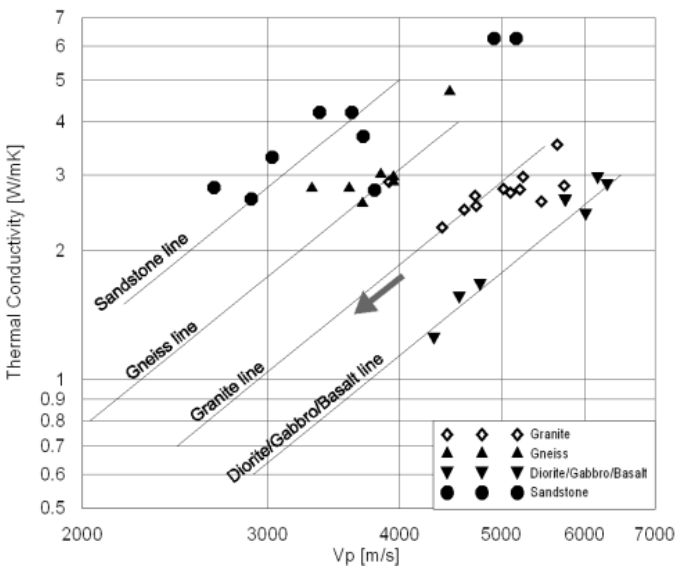

Figure 2: Correlations between thermal conductivity and compressional wave velocity. Points show the measured data, and lines are calculated by the defect model. Along the lines the defect parameter changes which demonstrates increasing the porosity.

The mineral composition for the defect model was expressed by the parameter A_s and the fracture influence was denoted by the defect *D*. Thus, the defect model is simple but can also describe the two important factors: mineral composition and the fractures/pores. Measured values fit to the model lines really well and the outliers can be explained easily. Again the correlation coefficients were high for both properties for granite/gneiss with high content of quartz and sandstone. For the granite/gneiss with low content of quartz, the correlation values were 0.7 and 0.68, which were moderate correlations. The inclusions and the defect model showed the same outliers: One sample of the granites, which was described as a granodiorite, lied between the granite and the basalt/diorite/gabbro line. One gneiss sample had a higher thermal conductivity, which can be explained by a higher content of quartz (Gegenhuber and Schoen, 2011). Dependence of degree of anisotropy can have an influence on the results because the mean values were used for the measured data. For further measurements or calculations this effect should be taken into account.

Both approaches were used to predict a correlation between thermal conductivity and compressional wave velocity which is controlled by:

- the influence of mineral composition (solid components) and

- the influence of fractures and cracks.

Both models worked specially for the magmatic rock really well. Comparing the correlation coefficients for both models showed that the inclusions model was slightly better for the granite/gneiss with high content of quartz. Granite/gneiss with low content of quartz showed a better correlation of the thermal conductivity for the inclusion model but a slightly better correlation of the compressional wave velocity for the defect model. For basalt/diorite/gabbro and sandstone both models showed the same correlation coefficients.

Correlation of thermal conductivity and formation factor for the carbonates are presented in Figure 3. Using the thermal conductivity for the two minerals: dolomite (7.0 $Wm^{-1}K^{-1}$) and calcite (4.0 $Wm^{-1}K^{-1}$) (Schoen, 2011), and the pore content (air = 0.025 $Wm^{-1}K^{-1}$) with the sample porosity, the corresponding aspect ratio α can be derived. *m* between 1 and 1.5 are typical for fractured rock and are low values in comparison to clastic rock types. m = 1.5 displays a mixture of fractured and interparticle porosity, while a higher value for m such as m = 2 is characteristic for sandstones and carbonate samples with interparticle porosity. In comparison to the aspect ratio, the controlling factor for the inclusions model was 0.01 for dolomite as well as for limestone. This aspect ratio was characteristic for thin penny-shaped cracks (Mavko et al., 2011).

(a) (b)

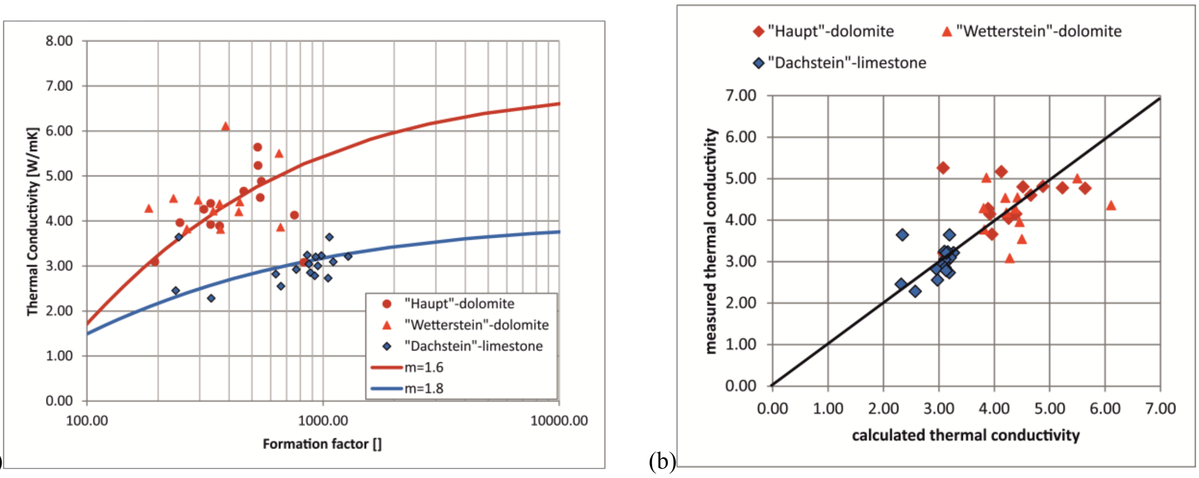

Figure 3: (a) Thermal conductivity versus formation factor and (b) correlation between measured and calculated thermal conductivity by the inclusions model. (a) Points show measured data and lines are calculated by using the inclusions model for thermal conductivity and the Archie equation for formation factor (Gegenhuber, 2013).

The used aspect ratio is α = 0.01 (= penny shaped cracks) and m was varied, which demonstrates different pore shapes. Figure 3(a) shows that limestone needs a different m (m = 1.8) from one for dolomite (m = 1.6). This can be explained due to the different pore geometry.

Figure 3(b) shows the measured thermal conductivity versus the calculated thermal conductivity from resistivity measurements. The developed equations were applied to the laboratory resistivity measurements. The limestone samples matched well. Only a few outliers of the dolomite can be found. The samples were not analysed by mineralogical methods. The lithology was characterized by literatures (geological maps). Therefore, the sample composition, such as ratios of limestone and/or dolomite, has not been determined.

5. APPLICATION ON BOREHOLE DATA

For a practical derivation of thermal conductivity using velocity or resistivity measurements (acoustic/soniclog, resistivitylog), calculated modelfff were approximated by regression functions. The results by the acoustic logs are shown in Table 2.

Rocktype	**Regression equations**
Sandstone	λ=1.123exp0.0003*v_p
Granite/Gneiss-lower quartz content	λ=9E-07*$v_p^{1.756}$
Granite/Gneiss-higher quartz content	λ=5E-08*$v_p^{2.14}$
Basic magmatic rocks	λ=6E-07*$v_p^{1.747}$

Table 2: Approximated equations using model calculations.

The derived equations (Table 2) allowed a direct transformation of acoustic log data into a thermal conductivity log for defined petrographic types. This is demonstrated for a borehole (KTB/Continental Deep Drilling Project) with metamorphic rocks.

The continental deep drilling project was situated in Germany and was carried out from 1986 until 1992. A wide spectrum of methods (logs and core analysis) has been measured. All data are still available on the internet (http://www.icdp-online.org/sites/ktb/). So this borehole was a good choice for an application and a direct verification by core data.

The rocks were metabasites and gneisses (alternately). The metabasite sections showed lower thermal conductivity than one of the granites. Therefore two equations for the two different petrographic types (xzxgranite and magmatic rocks) must be applied. Figure 4 shows the results of the inclusions model using acoustic logs as crossplots, one with the equation for magmatic rocks (metabasite) and one with the equation for granite/gneiss with low content of quartz. Using the petrographic relevant equations for the different sections gave good results. Values were in the same range as the measured thermal conductivity from the cores. Some of the gneiss values were not ideal and were mybe influenced by anisotropy, or other minerals. This is difficult to discuss in detail, because there was no information about the derivation of data from the samples and the lithology was characterized in literatures.

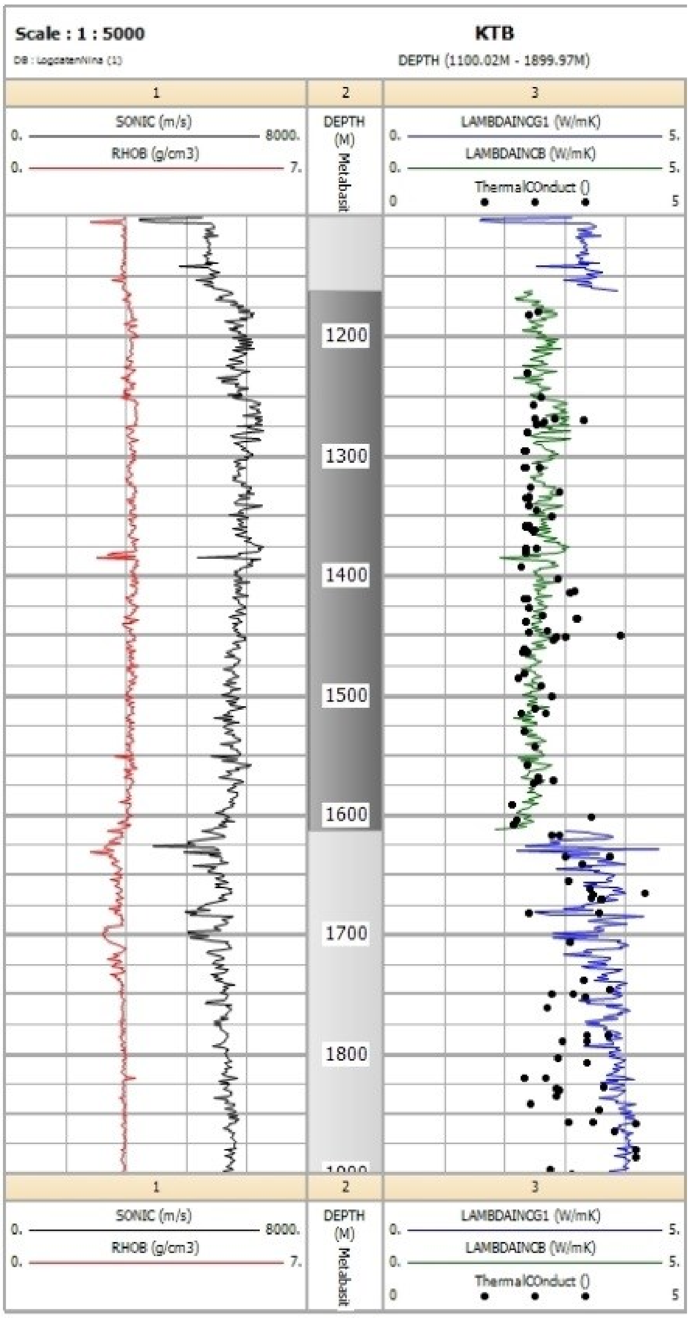

Figure 4: Results of the inclusions model using acoustic logs as crossplots: black line is sonic, red line is density. For lithology, dark grey is metabasite and grey is gneiss. For calculated thermal conductivity logs with the inclusions model using acoustic logs, blue line is gneiss, and green line is metabasite. Dots are thermal conductivity values from cores.

Since the calculated correlation lines of electrical resistivity for an application were described with single equations (Table 3), it is uneasy to be used as derivation tools. With these equations, the calculation of thermal conductivity log using resistivity log becomes possible.

Table 3: Correlation equations for dolomite (m=1.6) and limestone (m=1.8): y is thermal conductivity [$Wm^{-1}K^{-1}$], and x is $1/F^{0.5}$.

Rock type	
Dolomite	$y=11.10x^2-56.68x+7.21$
Limestone	$y=32.29x^2-28.65x+4.04$

For the application two wells in Austria were selected. Because of confidential reasons, the well names cannot be published. 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.

For a complete discussion the problem transferring laboratory data to borehole data must be cited as well. The derived equations will not give an exact thermal conductivity value at each point of the borehole. This is neither possible with borehole measurements. But the calculations should deliver continuous information about the thermal conductivity range with a good approximation. Therefore the equations are optimal tools which are easy applicable. Using log data for the calculations, depth related properties were automatically integrated and resumed.

Figure 5(a) displays the density, the resistivity and the calculated thermal conductivity log of the first well, where the lithology is "Dachstein"-limestone. The mean value of the measured thermal conductivity of the (dense) "Dachstein"-limestone in the laboratory was 2.98 $Wm^{-1}K^{-1}$. The mean value of the calculated thermal conductivity log at the depth between 1200 m and 1400 m was 2.77 $Wm^{-1}K^{-1}$, which weas close to the measured value.

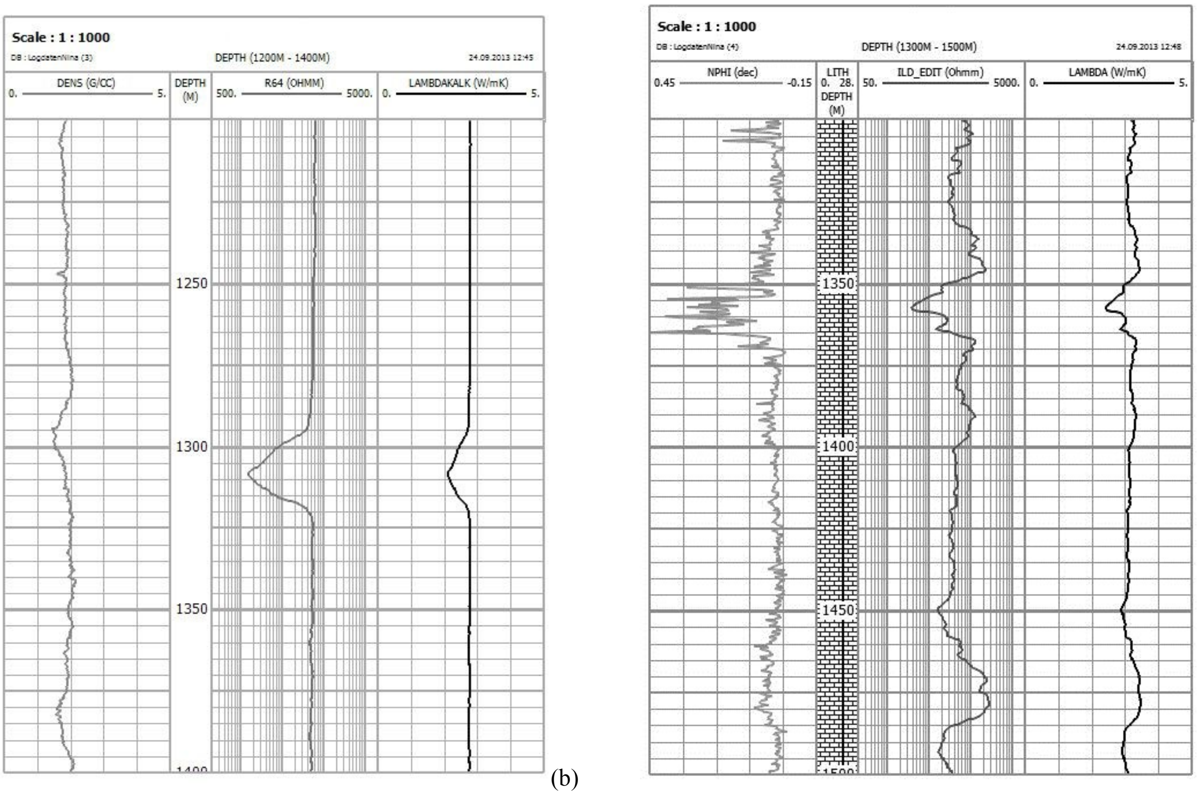

Figure 5: Log examples: (a) density [gcm^{-3}], resistivity (logarithmic) [Ohmm], and calculated thermal conductivity log [$Wm^{-1}K^{-1}$] (Lithology: "Dachstein"-limestone). (b) porosity [], induction log deep (logarithmic) [Ohmm], and calculated thermal conductivity [$Wm^{-1}K^{-1}$] (Lithology: "Schoeckel"-limestone).

The second well showed another type of carbonates at the depth between 1200 and 1600 m, where the lithology was the "Schoeckel"-limestone. The laboratory data of outcrop samples were also available. The mean of these values was 3.82 $Wm^{-1}K^{-1}$. The mean value of the calculated thermal conductivity at the depth between 1200 and 1500m was 3.13 $Wm^{-1}K^{-1}$.

6. CONCLUSION

Thermal conductivity is of fundamental importance for geothermal research and its applications. Direct measurements in most cases are only possible by using rock samples in the laboratory. In other situations in applied geophysics, an "indirect" determination, which means a derivation from other physical properties, would be a practical solution. Based on log measurements, such as electrical resistivity and elastic wave velocity, are such preferred measurements. Most correlations with thermal conductivity were characterized by scattered data and/or insufficient accuracy.

In the first part, it could be demonstrated that two factors with different influences controlled the relationship between thermal conductivity and electrical and elastic properties: The mineral composition and fractures, pores and other "defects". Therefore, a model concept must represent these two factors – called "petrographic coded model". The petrographic coded model developed equations for the correlations between thermal conductivity and compressional wave velocity/electrical resistivity was fitted and explained the laboratory data. 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/sonic logs depending on rock types.

In detail the comparison of measured and calculated data showed as follows:

- Correlations between compressional wave velocity/resistivity and thermal conductivity are controlled by mineral composition and fractures/pores.
- Inclusions models are one possibility to derive model-based relationships. They demonstrated both properties (mineral composition and fractures).
- A mathematical simplification of the derived curves from the inclusion model by a regression is possible and recommended for practical application.
- For carbonates the electrical resistivity is used where the Archie equation delivers good results for the correlations.

In order to implement these influences, a modular concept of model architecture was developed. It has two main steps:

Step 1: Modeling of mineral composition – this controls the petrographic code or rock type

Step 2: Modeling or implementation of fractures, pores etc.

For step 1 "mixing rules" or averaging equations gave a possibility of forward calculation. As a result of the variation of rock composition within one rock type in some cases, a pure empirical assumption of the "solid parameters is a more practical way and comparable to the practice of "matrix properties" in log interpretation.

For step 2 the inclusion model is a powerful tool using correlation between thermal conductivity and compressional wave velocity. The application on experimental data showed:

- The inclusion model had high correlation.
- The correlation was strongly influenced by the aspect ratio, particularly for fractured rocks.

Application of acoustic logs to derive a thermal conductivity log worked really well. By taking the petrographic code into account, calculated log data fitted to the measured core data.

For carbonates the Archie equation gave high correlations where the cementation exponent m represents the petrographic code and a variety in pore space. The two examples demonstrated for different carbonates (petrographic code) that the equations can be easily applied to thermal conductivity estimation, when electrical resistivity of rocks and water are available. The depth dependences can be seen also on the thermal conductivity log. Fracturing decreased in the resistivity as well as the 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 were different (this resulted from the different measuring principles and techniques), but the log-derived conductivity gave a good approximation and had an advantage of a continuous profile. It delivers also information in case of missing cores (for example fractured zones).

REFERENCES

Abdulagatov, I., Emirov, S., Abdulgatova, Z.Z. and Askerov, S.: Effect of pressure and temperature on the thermal conductivity of rocks, *Journal of chemical and engineering data*, **51**, (2006), 22-33.

Abdulagatova, Z. Abdulagatov, I. and Emirov, V.: Effect of temperature and pressure on the thermal conductivity of sandstone, *International Journal of Rock Mechanics & Mining Science*, **46**, (2009), 1055-1071.

Archie, G.E.: The electrical resistivity log as an aid in determining some reservoir characteristics, *Trans. Americ. Inst. Mineral. Met.*, **146**, (1942), 54-62.

Berryman, J.G.: Mixture theories for rock properties, in: *Rock physics and phase relations, a handbook of physical constants*, AGU (1995).

Budiansky, B. and O'Connell, R.: Elastic moduli of a cracked solid, *International Journal of Solids and Structures*, **12**, (1976), 81-97.

Burkhardt, H., Honarmand, H. and Pribnow, D.: First results of thermal conductivity measurements with a borehole tool for great depth, *KTB Report*, **90-6a**, (1990).

Fuchs, S.: Well-log based determination of rock thermal conductivity in the North German Basin, *PhD thesis*, Potsdam (2013).

Gegenhuber, N. and Schön, J.H.: New approaches for the relationship between compressional wave velocity and thermal conductivity, *Journal Applied Geophysics*, **76**, (2011), 50-55.

Gegenhuber, N.: Correlation of thermal conductivity and resistivity of carbonates from Austria. *Austrian Journal of Earth Science*, **106/2**, (2013), 37-44.

Hartmann, A., Rath, V. and Clauser, C.: Thermal conductivity from core and well log data, *International Journal of Rock Mechanics & Mining Science*, **42**, (2005),1042-1055.

Kukkonen, I.T. and Peltoniemi, S.: Relationships between thermal and other petrophysical properties of rocks in Finland, *Physics and Chemistry of the Earth*, **23**, (1998), 341-349.

Mavko, G., Mukerji, T. and Dvorkin, J.: The rock physics handbook. Cambridge university press (2011).

Ozkahraman, H., Slever, R. and Isik, E.: Determination of the thermal conductivity of rock from P-wave velocity, *International Journal of Rock Mechanics and Mining Science*, **41**, (2004), 703-708.

Popov, Y., Tertychnyi, V., Romushkevich, R., Korobkov, D. and Pohl, J.: Interrelations between thermal conductivity and other physical properties of rocks: Experimental data, *Pure and Applied Geophysics*, **160**, (2003),1137-1161.

Rybach, L. and Buntebarth, G.: Relationships between the petrophysical properties density, seismic velocity, heat generation and mineralogical constituents, *Earth and Planetary Science Letters*, **57**, (1982), 367-376.

Schoen, J.H.: Physical Properties of Rocks - a workbook, Elsevier B.V. (2011).

Singh, T., Sinha, S. and Singh, V.: Prediction of thermal conductivity of rock through physico-mechnical properties, *Building and Environmental*, **42**, (2007), 146-155.

Sundberg, J., Back, P.-E., Ericsson, L.O. and Wrafter, J.: Estimation of thermal conductivity and its spatial variability in igneous rocks from in situ density logging, *International Journal of Rock Mechanics & Mining Science*, **46**, (2009), 1023-1028.

Vosteen, H.-D.: The thermal regime of the Eastern Alps along the TRANSALP profile, *PhD thesis*, RWTH Aachen (2003).

Vosteen, H.-D. and Schellschmidt, R.: Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rocks, *Physics and Chemistry of the Earth*, **28**, (2003), 499-509.

Yasar, E., Erdogan, Y. and Güneyli, H.: Determination of the thermal conductivity from physic-mechanical properties, *Bulletin of Engineering Geology and the Environment*, **67**, (2008), 219-225.