Correlation of thermal conductivity and resistivity of carbonates from Austria

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Abstract

Thermal conductivity is one of the key properties used in geothermal projects and many other geoscientific fields. It is difficult, time consuming and uneconomic determining thermal conductivity in a borehole. Therefore, correlations with other petrophysical properties, which can easily be measured, are needed. For magmatic and metamorphic rocks a petrographic coded model is available for the correlation of thermal conductivity and compressional wave velocity. For carbonates this model cannot be applied in the existing form. Hence, a correlation of the thermal conductivity with the electrical resistivity/formation factor via the controlling factor porosity is presented for different carbonates from Austria. A forward calculation with the Archie equation for the formation factor and an inclusions model for thermal conductivity is used. The controlling factors m (cementation exponent) and R^{mi} respectively the aspect ratio are displayed and discussed. A trend between the two becomes visible. On the one hand, the correlation between thermal conductivity and formation factor for constant m is demonstrated, and on the other hand, for a constant aspect ratio α. The resulting equations out of the correlations depend on the lithology, reflect the main influences (mineralogy and porosity/fractures) and give the possibility of an application on resistivity logs in a further step, for the calculation of a "thermal conductivity" log.

Die Wärmeleitfähigkeit ist eine der Schlüsselgrößen in Geothermieprojekten und vielen anderen geowissenschaftlichen Bereichen. Es ist jedoch schwierig, zeitaufwändig und unwirtschaftlich die Wärmeleitfähigkeit im Bohrloch zu messen. Daher wird eine Korrelation mit anderen petrophysikalischen Parametern, die leicht im Bohrloch messbar sind, benötigt. Für magmatische und metamorphe Gesteine ist bereits ein petrographisch kodiertes Model für die Korrelation zwischen Wärmeleitfähigkeit und Kompressionswelle verfügbar. Dieses kann in der vorliegenden Form jedoch nicht auf Karbonate angewandt werden. Daher wird eine Korrelation zwischen Wärmeleitfähigkeit und elektrischem Widerstand/Formationsfaktor über den kontrollierenden Faktor, die Porosität, für Karbonatgesteine aus Österreich präsentiert. Eine Vorwärtsmodellierung mit der Archie Gleichung für den Widerstand und einem Inklusionsmodel für die Wärmeleitfähigkeit wurde dafür verwendet. Die kontrollierenden Faktoren m (Zementationsexponent) und R^{mi} beziehungsweise das „aspect ratio" α wurden betrachtet und einander gegenüber gestellt. Hierbei wurde ein eindeutiger Trend sichtbar. Dargestellt werden Korrelationen zwischen Wärmeleitfähigkeit und Formationsfaktor für konstantes m auf der einen Seite und ein konstantes α auf der anderen. Die daraus resultierenden Gleichungen hängen von der Lithologie und der Porosität ab und bieten in einem nächsten Schritt die Möglichkeit einer Anwendung auf Widerstandslogs um ein „Wärmeleitfähigkeitslog" zu berechnen.

1. Introduction

Thermal conductivity is one of the most important properties in regard to geothermal applications and a broad variety of geoscientific problems. Measuring thermal conductivity in boreholes is possible but time consuming and therefore uneconomic as well as insecure; particularly a good sensor contact with the borehole wall is needed (Burkhardt et al., 1990). One possible solution for this complex of problems could be the correlation between thermal conductivity and other petrophysical properties which can be measured easily in the borehole.

Previous studies aimed to express relationships between thermal conductivity and various petrophysical properties, such as density or seismic velocity. Most of the authors carried out regression analysis, such as Rybach and Buntebarth (1982), for the correlation of thermal conductivity and density, mineralogical constituents or heat generation. These data show the general trends for different rock types but they scatter and no further calculations have been carried out. A summary about thermal conductivity of rocks and minerals is given by Clauser and Huenges (1995), where the background of thermal properties, measuring techniques, and thermal conductivity data as well as correlations are presented.

Popov et al. (2003) divided a collection of data into six subcategories, from different silt and sandstone, to limestone and granite as wells 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 lines fit well to the data for porosity and electrical resistivity.

The general trend between thermal conductivity and density is published by Sundberg et al. (2009) for igneous rocks. In addition, they used density logs for the correlation. Hartmann et al. (2005) demonstrate the correlation of thermal conductivity and 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 these correlations are only valid for local conditions.

2705 different samples (plutonic rocky, dykes, volcanic rocks, sedimentary and metamorphic rocks) from Finland were measured and interpreted by Kukkonen and Peltoniemi (1998). They related thermal conductivity, density, magnetic susceptibility and compressional wave velocity. In general, they sum up that there is no general trend between thermal conductivity and other petrophysical properties and that data scatter.

In summary, there are many different approaches for the correlation of thermal conductivity and other petrophysical properties, but no general model concept is available. Gegenhuber and Schön (2012) published a first successful model concept for magmatic and metamorphic samples and sandstone samples for the correlation of thermal conductivity and compressional wave velocity. In this first approach, inclusion models and a simpler defect model were used for the calculations. Out of these, in a further step, a thermal conductivity log, using an acoustic log, can be calculated.

In this paper, carbonates are subject of investigation. The correlation of thermal conductivity and electrical resistivity via the controlling influence of porosity is studied. Carbonates provide a special challange for modelling in petrophysics although they represent an important group of rocks with respect to reservoir properties. Due to the fact that in many cases no acoustic log but resistivity logs are available, the correlation between thermal conductivity and specific electrical resistivity (and formation factor) was used. In addition, due to the small porosity of carbonate samples there was as a tendency towards a stronger influence of porosity on resistivity than on compressional wave velocity.

2. Measuring Method

For thermal conductivity measurements the thermal conductivity meter TK04 (from TeKa, Berlin), which is a non-steady state (transient) method (line source), was used. The needle acts as the heat source of defined energy. A temperature sensor in the middle of the needle measures the temperature as a function of time (Erbas, 2001). The half-space-line source and the sample are fixed by a contact pressure of 15bars (=1.5E6Pa). In order to establish an optimal heat flow between probe and sample a contact agent (here: Nivea cream) is applied. 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 (Erbas, 2001; Davis et al., 2007). The reproducibility is 1.5% in relation to conductivity. For this study, at least two measurement sets, each five single repeated values, are made. A weighted average is calculated and the standard deviation, which is between 0.01 and 0.2$Wm^{-1}K^{-1}$, is determined. Samples are measured dry and saturated. The difference is in the range of the reproducibility (because of the low porosity) and, therefore, for an interpretation not taken into account.

The specific electrical resistivity of a rock mainly depends on the water content in connected pores or fractures and on the specific resistivity of this water. 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. Temperature and resistivity or 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 2-electrode configuration were used. Samples are saturated with NaCl solution (20g NaCl with 1 l distilled water) under vacuum for one night. This salinity results in a water resistivity of 0.298Ohmm (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. Brass electrodes A, B send an alternating current into the sample; the voltage is measured as potential difference between the two electrodes M, N. For the best contact of sample and brass, small, thin and wet sponges are used. Only saturated samples with porosity can be measured, otherwise there is no conductive material (Gegenhuber, 2011).

The effective porosity is determined using the principle of Archimedes, where the samples are weighted dry, water saturated and under lifting. Samples are therefore dried overnight (12 hours) at 105°C. 12 hours lead to a mass stability. After determining the mass dry, samples are again saturated 12 hours with a solution of 1g NaCl and 1l distilled water. Mass saturated and buoyancy are measured.

All measurements were repeated three times for verification and calculation of a mean value and all analyses were carried out at room temperature.

3. Samples

Table 1 gives an overview of the samples, mainly from Austria, and the measured data (thermal conductivity, electrical resistivity, formation factor and porosity). The carbonates in-

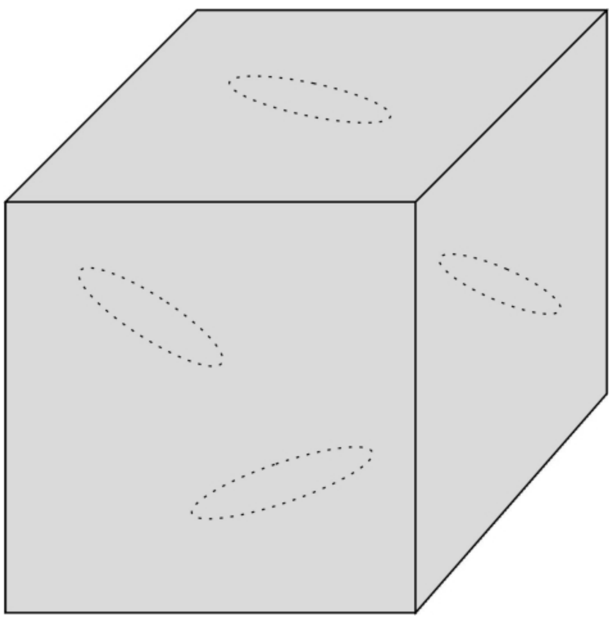

Figure 1: Illustration of the inclusions model (inclusions are presented as ellipsoids).

Rocktype	λ	Φ	R_0	F
	$Wm^{-1}K^{-1}$	[]	Ohmm	
Dolomite (Devonian)	3.8	0.043	92.2	451
Dolomite (Devonian)	3.9	0.002	138.6	633
Dolomite (Devonian)	3.5	0.006	109.2	512
"Haupt"-dolomite	3.9	0.019	84.5	378
"Haupt"-dolomite	5.2	0.012	131.1	549
"Haupt"-dolomite	4.9	0.012	102.6	418
"Haupt"-dolomite	4.7	0.021	116.2	443
"Haupt"-dolomite	5.6	0.014	257.2	884
"Haupt"-dolomite	3.1	0.009	236.8	867
"Haupt"-dolomite	4.5	0.012	126.0	446
"Haupt"-dolomite	4.0	0.036	59.6	207
"Wetterstein"-dolomite	5.5	0.011	128.1	523
"Wetterstein"-dolomite	3.8	0.018	90.1	380
"Wetterstein"-dolomite	4.2	0.012	86.2	349
"Schöckel"-limestone	4.2	0.005	94.0	455
"Schöckel"-limestone	7.2	0.004	113.9	554
"Schöckel"-limestone	6.2	0.002	179.4	919
"Schöckel"-limestone	3.4	0.001	124.0	681
"Schöckel"-limestone	3.1	0.003	151.7	774
"Schöckel"-limestone	3.5	0.001	198.6	825
"Schöckel"-limestone	2.9	0.006	177.2	898
"Schöckel"-limestone	3.1	0.003	98.0	504
"Schöckel"-limestone	3.1	0.007	195.4	1037
"Schöckel"-limestone	2.7	0.007	133.6	581
"Dachstein"-limestone	2.7	0.008	239.9	933
"Dachstein"-limestone	3.6	0.001	296.2	1066
"Dachstein"-limestone	3.0	0.008	268.4	980
"Dachstein"-limestone	3.2	0.009	324.7	1162
"Dachstein"-limestone	2.9	0.011	314.5	1106
"Dachstein"-limestone	3.0	0.009	258.8	907
"Dachstein"-limestone	2.9	0.012	158.1	623
"Dachstein"-limestone	3.2	0.011	149.2	644
"Dachstein"-limestone	2.8	0.009	166.4	688
"Dachstein"-limestone	3.2	0.011	281.7	1181
"Dachstein"-limestone	3.6	0.032	55.6	237
"Dachstein"-limestone	5.6	0.016	86.2	375
"Dachstein"-limestone	2.6	0.009	171.7	746
"Dachstein"-limestone	3.2	0.008	229.6	999
"Dachstein"-limestone	2.8	0.006	220.4	957

Table 1: Measured data (λ=thermal conductivity (dry), φ=effective porosity, R_0=electrical resistivity, F=formation factor).

vestigated in this study have generally low porosities.

The “Dachstein”-limestone is from a stone pit in Ebensee (Upper Austria), 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 three samples are from the Northern Calcareous Alps). The “Schoeckel”-limestone samples (Graz Paleozoic) are from a project with the Austrian Geological Survey (GBA) and are partially from drilling cores from the GBA and from stone pits from lower Styria. The dolomite samples (Devonian, Graz Paleozoic)) are also from pits from lower Styria (Graz Paleozoic). All samples from the stone pits were fresh and had no alteration marks.

4. Forward calculations of the relationship

For the relationship between formation factor, representing the electrical conductivity or resistivity, and thermal conductivity, a forward calculation was tested. The connecting parameter for this relationship is the porosity, which decreases resistivity (when the pores are fully saturated) and thermal conductivity. It is important to mention, that the formation factor (equ. 1) is mainly dependent on the porosity and the pore structure and is independent of the mineral composition (dolomite and calcite are both isolators). In contrast to the thermal conductivity, the mineral composition has an influence as well as the porosity. At this particular time it is not clear whether the pore structure can also influence thermal conductivity.

The two properties are calculated with different algorithms:

- the formation factor is calculated using Archie’s equation (1942); the diversity of pore geometry is implemented by different exponents m
- thermal conductivity is calculated with an inclusions model; the diversity of pore geometry is implemented by different aspect ratios (α).

Archie’s law (eq. 1) (1942), for water saturated clean rocks gives a direct link between specific rock resistivity (R_0), porosity Φ and pore water resistivity (R_w), with which the sample is saturated:

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

where *m* is the cementation exponent. As a result of the complexity and diversity of pore structures the exponent *m* in carbonates cannot be as clearly determined as in clastic rocks. Systematic studies of these pore types have been published, for example, by Focke and Munn (1987) and Fleury (2002) and show a broad spectrum of exponents.

For modelling the thermal conductivity, an inclusions model, with non-spherical inclusions randomly oriented (figure 1), is taken as a basis. The equation of Clausius-Mossotti (see Berrymann, 1995) gives the following thermal conductivity for the inclusions model:

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

where

$$R^{mi}=*\frac{1}{9}\left(\frac{1}{(L_{a,b,c}*\lambda_i+(1-L_{a,b,c})*\lambda_s)}\right) \quad (3)$$

λ_i is the thermal conductivity of the inclusion
λ_s is the thermal conductivity of the solid mineral composition
R_{mi} is a function (equ. 3) of the depolarization exponents L_a, L_b, L_c where the subscript a, b, c refer to the axis direction of the ellipsoids. Depolarization exponents are related to the aspect ratio (Berryman, 1995) where $L_a+L_b+L_c=1$. 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).
Sen (1981) recommends the following approximation for plate-like objects (*a=b>>c*)

$$L_c=1-\frac{\pi}{2}*\frac{c}{a}=1-\frac{\pi}{2}*\alpha \quad (4)$$

where $\alpha=\frac{c}{\alpha}$ is the aspect ratio.
This can be applied for an estimate of L_c. In a second step, the results are

$$L_a=L_b=\frac{1-L_c}{2}=\frac{\pi}{4}*\alpha \quad (5)$$

Table 2 gives an overview of some different aspect ratios and the resulting depolarization exponents

a=c/a	$L_a=L_b$	L_c
0.1	0.0785	0.8429
0.05	0.0393	0.9215
0.01	0.0079	0.9843
0.005	0.0039	0.9921

Table 2: Aspect ratios and resulting depolarization factor.

Based on the model concept, analyse of experimental data for thermal conductivity can be realized in two steps:

Step 1: Equation (3) gives the sample parameter R^{mi} for each sample; this parameter is controlled by the thermal conductivity of the constituents, which are taken from literature, porosity and inclusion shapes (aspect ratio α).

Step 2: Correlation of thermal conductivity and formation factor; using 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, the corresponding aspect ratio α can be derived. Two cases were regarded: constant m and varying aspect ratio and constant aspect ratio and varying *m*.

5. Interpretation of results

Because thermal conductivity is strongly controlled by the different mineral properties, a separate calculation is necessary for limestone (calcite) and dolomite. However, concerning the formation factor, the two minerals act as insulators and, therefore, have the same effect.

Step 1: For a better understanding of the controlling factors m (Archie equation) and R^{mi} (inclusions model) are plotted in figure 2. For each experimental data set the exponent m from porosity and formation factor and the R^{mi} using the conductivities of the components and the porosity with equation (3) was calculated and plotted. A trend between these two becomes visible.

For the correlation between m and R^{mi}, which is controlled by the aspect ratio and the porosity, two approaches were displayed. On the one hand, a constant m is used, which leads to the grey line for the dolomite (y=-19.5x+1.7) and the black for the limestone (y=-9x+1.7) and, on the other hand, different values for m (1.5, 1.6 and 1.7) are tested, which lead to the grey dashed lines (y=-7.5x+1.5; +1.6; +1.7). Both can describe the main influences of m and R^{mi}, where the grey and black correlation lines depend mainly on the rock type, including the mineralogical part and the dashed lines mainly de-

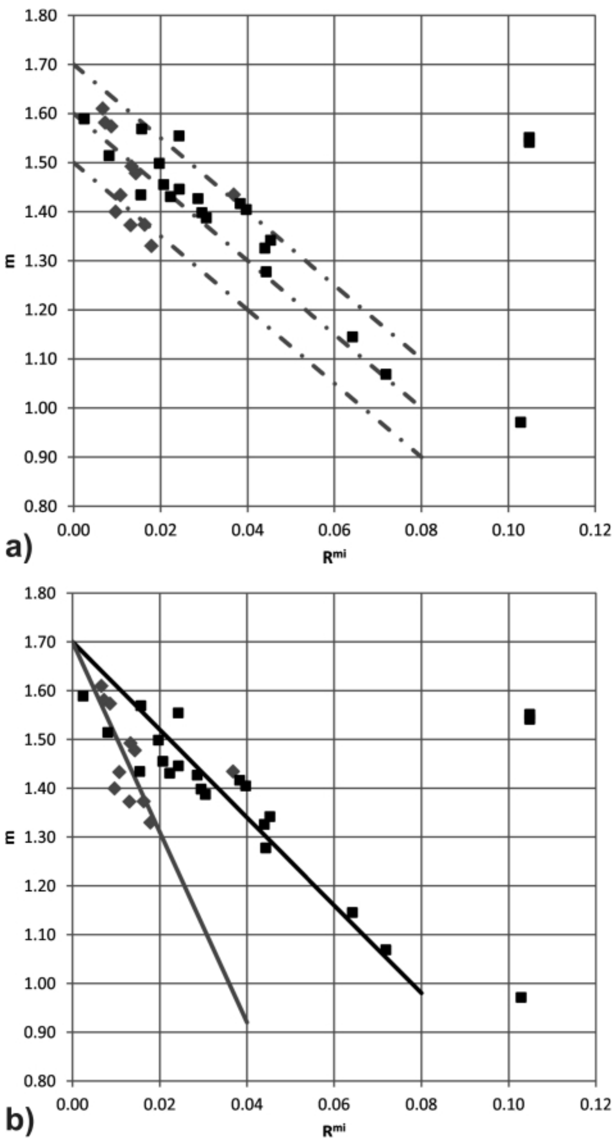

Figure 2: m versus R^{mi}, points: black: limestone, grey: dolomite, lines show correlation between the two controlling factors, a: dashed lines display varying m, b: full lines show a constant m.

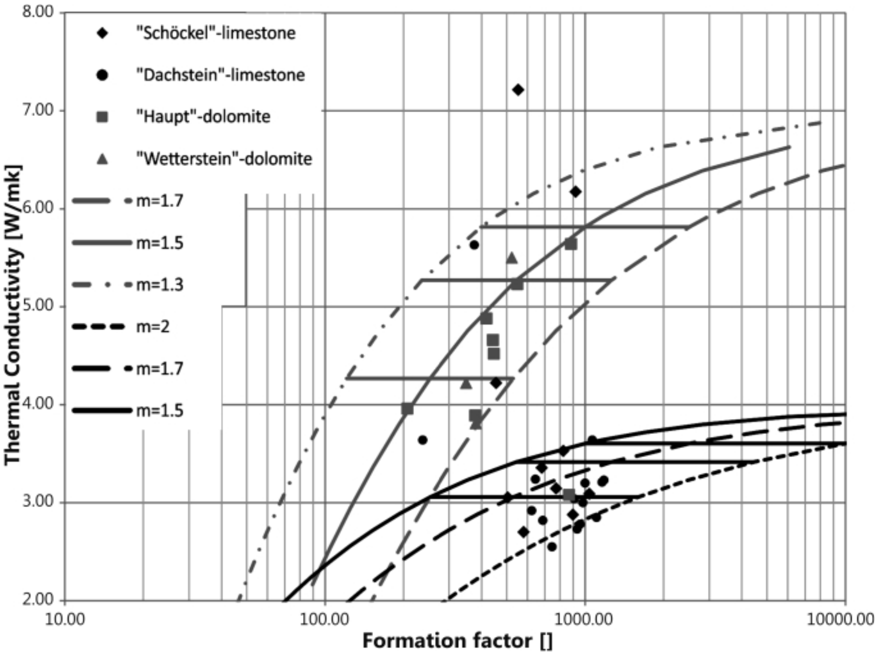

Figure 3: Thermal conductivity [$Wm^{-1}K^{-1}$] versus formation factor [], lines show calculated results with Archie equation and inclusions model, constant α=0.01 and varying m. Connective lines show a porosity of 0.01, 0.02 and 0.03, grey: dolomite, black: limestone.

monstrate the influence of the pore space geometry.

Step 2: Figure 3 and 4 shows the correlation between thermal conductivity and formation factor, including the calculated results from the models. Lines show the results for different m values for the Archie equation and calculated thermal conductivity with the inclusions model for constant aspect ratios. Points show measured data for different limestone and dolomite types of Austria. Two approaches were used:

- Constant α and varying m (Figure 3)
- Constant m and varying α (Figure 4)

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 and 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 is 0.01 for our calculations for dolomite as well as for limestone. This aspect ratio is characteristic for thin penny-shaped cracks (Mavko et al., 2011).

Limestone samples are between *m*=1.5 and *m*=2 , in comparison to the dolomite which is between *m*=1.7 and 1.3, both displayed with an aspect ratio of 0.01. If the aspect ratio is increased to 0.02, the result would be a higher m value for both rock types (limestone: between 2.4 and 2.2 and dolomite: between 2 and 1.5). This demonstrates that both are very sensitive to the aspect ratio and hence need to be chosen well.

The second calculation, for the description of thermal conductivity and formation factor, were carried out using different aspect ratios and a constant value for m (Figure 4).

Figure 4 shows the influence of the aspect ratio α as a function of the cementation exponent m. Depending on the rock type, higher and lower aspect ratios for the best fit are needed. *M* is chosen with 1.7 which demonstrates a mixture of interparticle and fractured porosity. Dolomite values lie between an aspect ratio of 0.005 and 0.01, which displays a mixture of thin penny shaped cracks and fine cracks (Mavko et al., 2011). Limestone samples with a lower thermal conductivity show the best fit with α=0.01 and α=0.02 (thin penny shaped cracks).

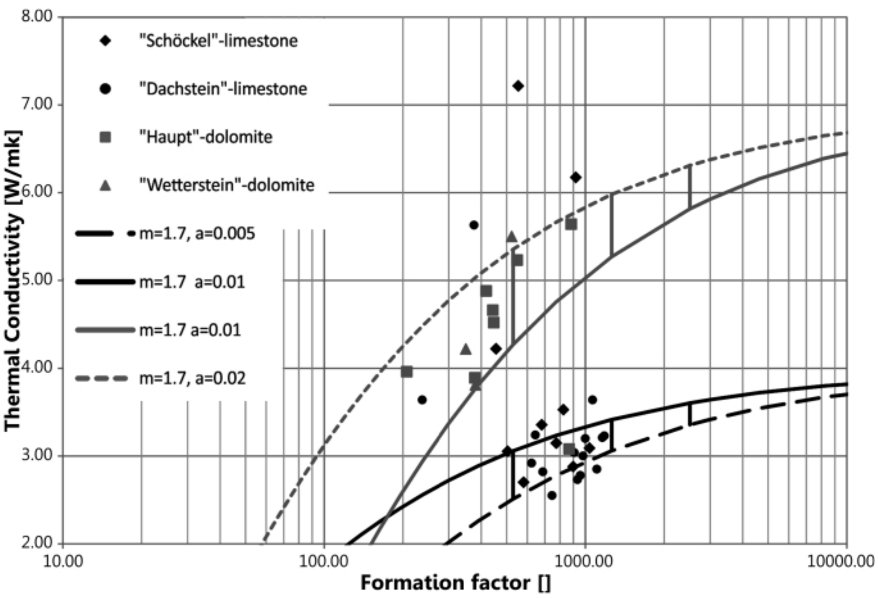

Figure 4: Thermal conductivity [$Wm^{-1}K^{-1}$] versus formation factor [], lines show calculated results with Archie equation and inclusions model, constant m=1.7 and varying α, grey: dolomite, black: limestone, Connective lines show a porosity of 0.01, 0.02 and 0.03.

6. Resulting equations for the application

For the derivation of the equations for an application a better formulation of the correlations is used. With the resulting equations, a calculation of thermal conductivity out of resistivity logs becomes possible. Due to the correlation of porosity and formation factor (eq. 6), figure 5 results.

$$\Phi=\frac{1}{\sqrt{F}} \qquad (6)$$

Out of the calculated correlation lines the following equations can be determined for further applications:

Figure 6 displays the correlation between thermal conductivity and $\sqrt{\Phi^m}$ respectively $1/\sqrt{F}$ with constant aspect ratio (α=0.01) and varying m. Resulting equations are:

7. Conclusion

Using Archie's equation and an inclusions model for determining electrical resistivity and thermal conductivity, the coupled influence of mineral composition and porosity/fracturing can be demonstrated. Both parameters are dependent on the porosity, which decrease with increasing porosity. Correlations show a sensitivity concerning the aspect ratio. For dolomite the aspect ratio, with constant cementation exponent *m*, is between 0.005 and 0.01 and demonstrates a mixture of thin penny shaped cracks and fine cracks. Limestone, in contrast, has a higher aspect ratio of 0.01 and 0.02 and, therefore, more "thin penny shaped cracks".

If the aspect ratio is constant at 0.01 for both rock types, m is between 1.5 and 2 for limestone, which means a mixture of fractured and interparticle porosity. Dolomite has an m value between 1.3 and 1.7 with constant aspect ratio, which is more typical for fractured rocks.

In summary, it can be said, that the calculations can display the correlation of thermal conductivity and electrical resistivity or formation factor. Both types (constant α or constant *m*) can be used, but more data will be needed for a verification of the calculations.

Further data may help to decide if one of the two approaches is better for the application. Furthermore, the upscaling effect must be taken into account in further research. Additio-

Rock type	a=001	a=0.005	a=0.02
Limestone	y=54,50*x²-39.16*x+4.1	y=15.82*x²-24.37*x+4.1	
Dolomite	y=107.58*x²-72.15*x+7.2		y=27.43*x²-42.52*x+7.1

Table 3: Resulting equations for the application of the correlation, $x=1/\sqrt{F}$ and $y=\lambda$ in $Wm^{-1}K^{-1}$ with constant m=1.7.

Rock type	m=2 (lim.)/ m=1.3 (dol.)	m=1.7	m=1.5
Limestone	y=85.72*x²-38.94*x+4.0	y=15.82*x²-24.37*x+4.1	y=-4.32*x²-17.15*x+4.1
Dolomite	y=-8.17*x²-36.0*x+7.5	y=107.58*x²-72.15*x+7.2	y=-23.24*x²-46.1*x+7.3

Table 4: Resulting equations for the application of the correlation, $x=1/\sqrt{F}$ and $y=\lambda$ in $Wm^{-1}K^{-1}$ with constant α=0.01.

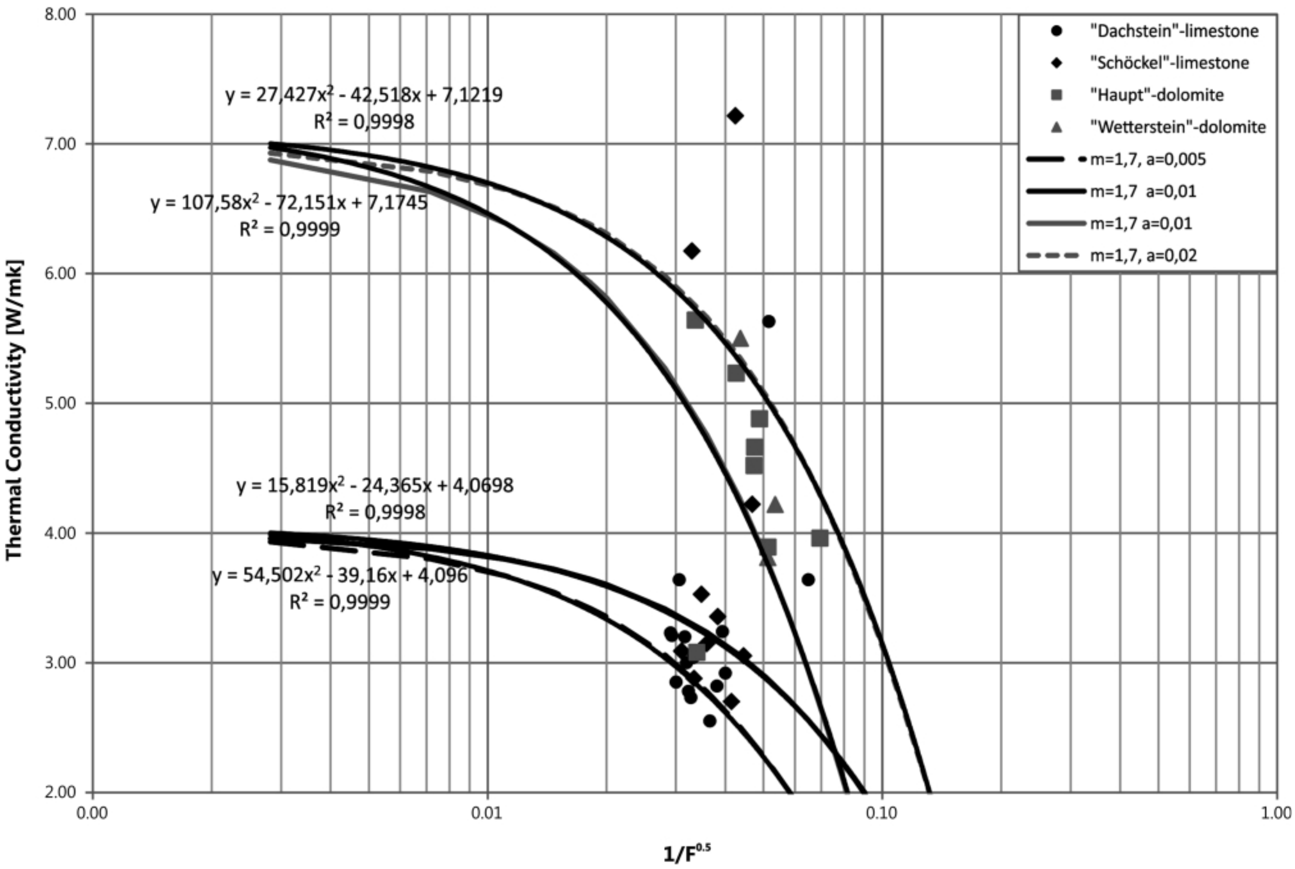

Figure 5: Thermal conductivity versus $\sqrt{\Phi^m}$ respectively $1/\sqrt{F}$, constant m and varying α, grey: dolomite, black: limestone.

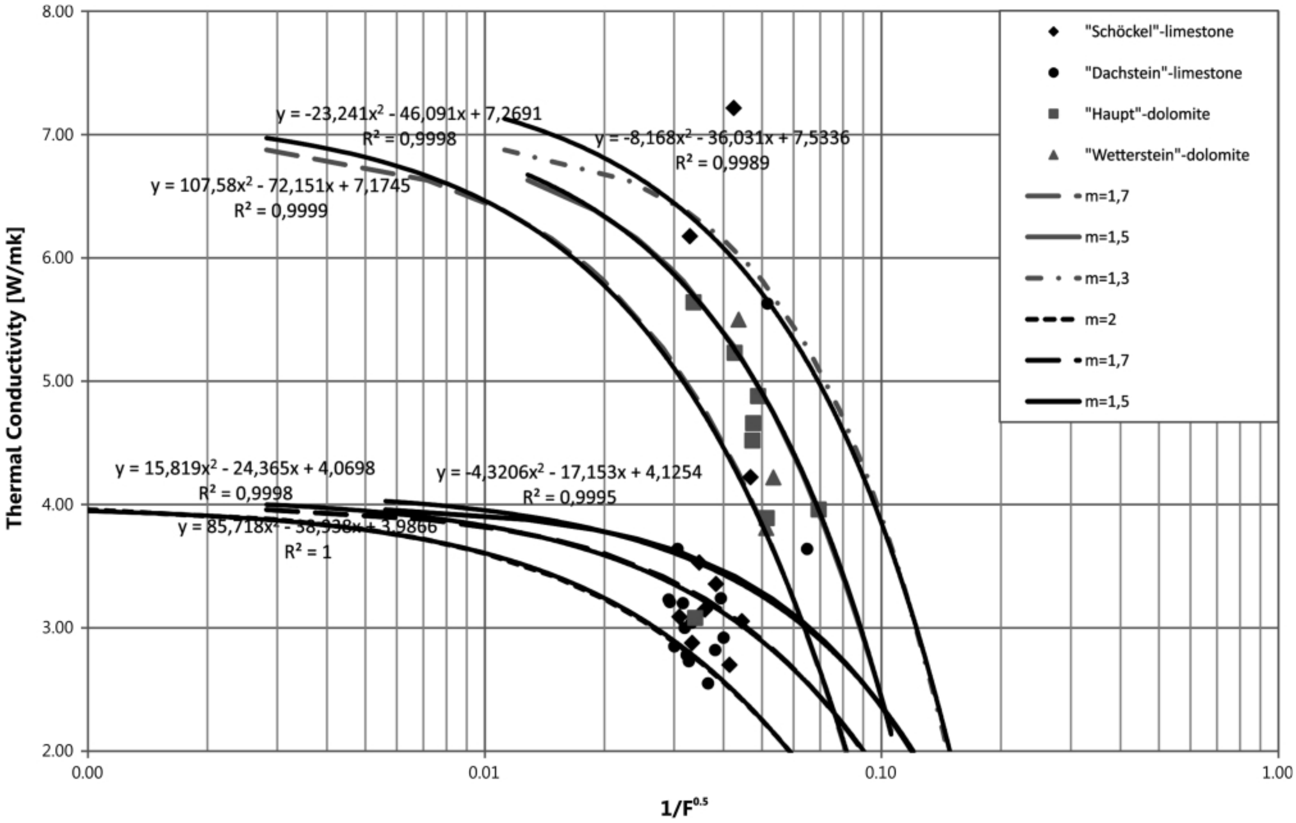

Figure 6: Thermal conductivity versus $\sqrt{\Phi^m}$ respectively $1/\sqrt{F}$, constant α and varying m, grey: dolomite, black: limestone.

nally, information about the pore type can be obtained, because different m or aspect ratios display various pore types.

The resulting equations out of the correlations can further be applied in geothermal projects, where thermal conductivity is an important key property. The required Information is, therefore, needed the rock type and a resistivity log as well as the resistivity of the water for the calculations of the formation factor. Using the derived equations a "thermal conductivity" log can be calculated. This paper presents, therefore, a first approach where a lot of work still needs to be carried out for an improvement of the calculations and an optimal application in the field.

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