doi: 10.22564/brjg.v5i2.2230

*Revista Brasileira de Geofísica; 1987, Vol. 5, 103-109*

# LABORATORY THERMAL CONDUCTIVITIES APPLIED TO CRUSTAL CONDITIONS

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Using a divided bar apparatus, the thermal conductivity of some sedimentary and some common crystalline rock samples has been investigated. The divided bar can be heated by a guard heating system up to 600°C, and a contact pressure of about 50 MPa can be applied. The sandstones (Upper Carboniferous) exhibit a remarkable nonlinear increase of the thermal conductivity with pressure up to about 10 MPa. Siltstones and the crystalline rocks demonstrate a linear pressure dependence of the conductivity within the applied pressure range. The dependence of the conductivity upon temperature is high for sandstones and quartz-bearing rocks. The most finegrained siltstone and some crystalline rocks show a weak temperature sensitivity of the conductivity. If the thermal conductivity of sedimentary rocks is applied for heat flow determination, a difference of up to 20% may arise when the variation of conductivity with pressure and temperature is applied or neglected. Applying the measured thermal conductivity of crystalline rocks, the thermal conductivity vs. depth is estimated for Precambrian and Phanerozoic areas.

Utilizando-se de um dispositivo de barra dividida, estudou-se a condutividade térmica de amostras de algumas rochas sedimentares e de algumas rochas cristalinas comuns. A barra dividida pode ser aquecida por uma manta de aquecimento até 600°C, e um pressão de contato da ordem de 50 MPa pode ser aplicada. Os arenitos (Carbonífero Superior) apresentam um notável crescimento não-linear da condutividade térmica como função da pressão até aproximadamente 10 MPa. Siltitos e rochas cristalinas apresentam uma dependência linear da condutividade com a pressão dentro do intervalo de pressões aplicadas. A dependência da condutividade térmica com a temperatura é alta para os arenitos e para as rochas contendo quartzo. A maioria dos siltitos e algumas rochas cristalinas mostram que a condutividade é pouco sensível à temperatura. Quando a condutividade térmica de rochas sedimentares é utilizada em determinação de fluxo térmico, diferenças de até 20% podem ocorrer se a variação da condutividade térmica com a pressão for considerada ou desprezada. Utilizando-se das medidas de condutividade térmica em rochas cristalinas, a variação da condutividade térmica com a função de profundidade é estimada para áreas Pré-cambrianas e Fanerozóicas.

**(Traduzido pela Revista)**

## INTRODUCTION

The heat conductivity of rocks is evidently of importance in order to determine the heat flow density or for the downward continuation of temperature using the surface heat flow density.

Since the temperature may reach about 600°C at the base of the crust and the pressure increases to about 1 GPa, the heat conductivity must be known as a function of both temperature and pressure. There are only a few data of common crustal rocks available which provide partial derivatives of the thermal conductivity of the same rock sample to both the temperature and the pressure. A data collection of heat conductivities of crustal rocks is given by Cermák & Rybach (1982).

The measurement of thermal properties in boreholes is not well developed, so that in-situ measurements or simple estimation are not suitable for constructing crustal temperature models. On the other hand, laboratory experiments yield the properties of more or less small samples and the application of the values from these to thick crustal layers implies uncertainties due to physical or chemical heterogeneities that are not apparent in the samples. Moreover, the effects of temperature as well as pressure on the thermal conductivity can reduce its value by 50%. The temperature and pressure dependence of the thermal conductivity is therefore not negligible.

## EXPERIMENTAL

The thermal conductivity was measured using a divided bar apparatus. This heat flow meter method is described by, e.g., Francl & Kingery (1954). Each section of the divided bar is heated by a guard heater, i.e. around the heat source, the heat sink, the sample and the standard. This heating system is well insulated by a fibrous ceramic material. The guard heater system minimizes radial heat flow. The diameter of the divided bar is 50 mm and the sample thickness does not exceed 10 mm which means that the heat flux penetrates about 10 grains. The mean grain size of the samples used is about 1 mm with the exception of one pyroxenite which has a mean grain size of 2 mm with some grains reaching 5 mm Ø. The temperatures at the surface boundaries between heat source and sample, between sample and standard probe and finally between standard probe and heat sink are measured using three thermocouples in each boundary. This divided bar device is put under a hydraulic press to apply uniaxial stresses of up to about 60 MPa.

The samples which are investigated are analysed in Table 1. The crystalline rocks derive from Scotland, the Eifel/FRG, the Black Forest/FRG and the Alps/Switzerland and Italy. The mineralogical composition as well as petrophysical properties are given. With the exception of sample nº 6, the grain sizes do not exceed 2 mm. The seismic velocity $v_p$ is determined under hydrostatic pressure and the grain sizes are estimated at the samples prepared for heat conductivity measurements using a magnification of 40 x.

The sedimentary samples derive from a borehole, in the Ruhr Basin/FRG, which encountered Westphalian A (Upper Carboniferous). Three rock types are used: medium-grained quartzose light grey sandstones containing up to 10% feldspar grains, fine-to medium-grained sericitic grey sandstone which is flasery with thin coaly and clayey flasers and lenses and 5 to 10% feldspar grains, and finally, strongly argillaceous grey to dark grey siltstone with about 50% grains.

## EXPERIMENTAL RESULTS

From various papers it is known that at low pressure the thermal conductivity of many rocks increases nonlinearly with increasing pressure and above about 10 MPa a linear relation exists, e.g. Woodside & Messmer, 1961; Hurtig & Brugger, 1970.

In general, the thermal conductivity of sedimentary rocks can be more sensitive to pressure variations than that of crystalline rocks. This implies that the nonlinear pressure effect is due rather to the structure of the samples than to the mineral constituents. Some samples of common rocks are presented in Fig. 1. If any nonlinear increase of the conductivity with pressure is observed at low pressure, this effect is supposed to be mainly due to the specimen preparation which causes microcracks and not a typical matrix property.

Fig. 1 shows the pressure dependence of the thermal conductivity of a dry Upper Carboniferous sandstone from the Ruhr basin/FRG with a porosity of 3% (nº 14, Tab. 1). A remarkable increase of the conductivity of about 20% is observed at increasing stresses of up to 10 MPa. The most fine-grained strongly argillaceous siltstone of the Carboniferous Ruhr basin shows a weak, and within the pressure range, linear change in the thermal conductivity, the same as shown by crystalline rocks at pressure variations (Fig. 1). The nonlinear effect of stress is summarized in Table 2 as the ratio of the conductivity at p = 0.5 MPa and 10 MPa, respectively.

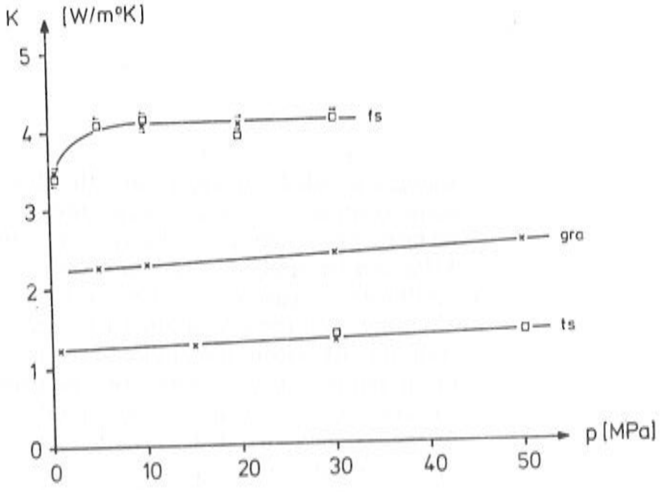

**Figure 1** — Thermal conductivity dependence on contact pressure of samples of (fs) fine-grained sandstone, (ts) siltstone, and (gra) granite at about T = 40°C — □ repeated measurement at (→) increasing, resp. (←) decreasing pressure.

The linear increase of the thermal conductivity with pressure is summarized for some sedimentary as well as crystalline rocks in Table 3. The values are given as constant partial derivates for each rock type:

$$\frac{1}{K_o}\left(\frac{\partial K}{\partial p}\right)_T \approx \text{constant} \tag{1}$$

where $K_o$ is the conductivity at a contact pressure of 10 MPa. This value is constant to a first approximation up to a pressure of 60 MPa.

The temperature dependence of the thermal conductivity is determined by applying the Fourier equation for thermal conduction. It is valid up to a temperature at which the contribution of radiant heat transfer exceeds the inaccuracy of the apparatus used for measurement. This temperature is also dependent on the rock material, whether it is opaque or translucent for infrared radiation. The rock samples investigated up to 600°C do not show a contribution of radiant heat transfer.

The thermal conductivity of crystalline rocks (K) falls off with temperature (T). Leibfried & Schlömann (1954) showed that for temperatures above the Debye temperature

$$K \sim T^{-1} \tag{2}$$

for a structural perfect monatomic crystal. Since the mineral components of a rock are imperfect, i.e. more or less disordered, the phonon free path is reduced

**Table 1** – Composition and petrophysical properties of the samples used for thermal conductivity measurements

| | sample | $\rho$ (g/cm$^3$) | $V_p$ at 100 MPa (km/s) | mean/max. grain size (mm) | $\phi$ (%) | volume per cent of minerals | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | qu | or | plg | ms | bio | am | cpx | opx | ol | ser | ore | chl | acc |
| 1 | qu-diorite | 2.74 | 6.0 | 0.7/1.8 | | 13 | 27 | 26 | 11 | 13 | 7 | | | | | | | |
| 2 | granite | 2.69 | 5.9 | 0.8/2 | | 12 | 35 | 24 | 15 | 8 | 3 | | | | | | | |
| 3 | quartzite | 2.64 | 6.5 | 0.7/1 | | 90 | 7 | 2 | | | | | | | | | | |
| | gabbro[1] | 2.99 | | | | | | 2 | | | 35 | | 19 | | | 2 | 38 | 4 |
| 4 | olivinite | 3.24 | 7.9 (200MPa) | 0.3/0.8 | | | | | | | | 24 | 2 | 70 | | 4 | | |
| 5 | peridodite | 3.29 | 8.1 | 2/4 | | | | | | | | | | 93 | | 7 | | |
| 6 | pyroxenite | 3.09 | 7.7 | 3/6 | | | | | | | | | 60 | | 26 | 4 | | 10 |
| 7 | pyroxenite | 3.07 | 7.3 | 1.4/2 | | | | | | | 13 | | 56 | | 15 | 6 | | 10 |
| 8 | gabbro | 2.96 | 7.1 | 0.1/0.8 | | 2 | | 34 | | | 59 | | | | | 4 | | 1 |
| 9 | gabbro | 3.06 | 7.0 | 0.6/2 | | | | 45 | | 8 | 44 | | | | | 3 | | |
| 10 | granite | 2.60 | 5.9 | 1/2 | | 44 | 22 | 25 | 6 | | | | | | | 3 | | |
| 11 | granite | 2.62 | 6.1 | 1/2.5 | | 35 | 20 | 33 | | 12 | | | | | | | | |
| 12 | granite | 2.61 | 6.5 | 0.7/1.8 | | 41 | 23 | 26 | | 9 | | | | | | 1 | | |
| 13 | medium-grained sandstone | 2.62 | 5.2[2] | 0.4/0.6 | 4.3 | 80 | 9 | 1[3] | | | | | | | | | | 10 (ms, carbonate |
| 14 | fine-grained sandstone | 2.67 | 5.1[2] | 0.2/0.4 | 3.0 | | | | | | | | | | | | | |
| 15 | siltstone | 2.68 | 4.7 | < 0.002/ 0.063 | | constituents: qu, ms, illite, kaolinite, siderite[3] | | | | | | | | | | | | |

[1] after Mirkovich & Soles (1978),

[2] water-saturated,

[3] mean values after Esch (1962) which aggrees macroscopically with the samples

$\rho$ - Density of the matrix, $v_p$ - compressional wave velocity, $\phi$ - porosity, qu - Quartz, or - orthoclase, plg - plagioclase, ms - muscovite, bio - biotite, am - amphibole, cpx - clinopyroxene, opx - orthopyroxene, ol - olivine, ser - serpentine, chl - chlorite, acc - accessories.

which results in a higher thermal resistivity than that of perfect crystals. By analogy with Matthiessen's rule for electrical resistivity, Ross et al. (1984) define the thermal resistivity

$$K^{-1} = A_{st} + A_{ph}\,T \qquad (3)$$

where the quantity $A_{st}$ is temperature independent and associated with structural disorder. $A_{ph}$ is the factor of proportionality between thermal resistivity and temperature after Leibfried & Schlömann (1954). Eq. (3) is valid above the Debye-temperature, so that measurements near room temperature may deviate from this formula in some cases.

**Table 2** – The relative change of thermal conductivity of Upper Carboniferous rocks of the Ruhr basin/FRG with pressure between p = 0,5 MPa and p = 10 MPa.

| sample nº | rock | $K_{0.5}/K_{10}$ |
|---|---|---|
| 13 | medium-grained sandstone | 0.74 . . 0.96 |
| 14 | fine-grained sandstone | 0.8 . . 1.0 |
| 15 | siltstone | 0.94 . . 1.0 |

The concept of Eq. (3) cannot be applied to sedimentary rocks, in general. Porosity and impurity introduce additional thermal resistivities which are not considered in Eq. (3). However, if all these additional effects are assumed to be independent of temperature to a first approximation, $A_{st}$ can be replaced by a more general, but undefined quantity B which is valid within the limited temperature range at which both quantities are determined:

$$K^{-1} = B + A_{ph}\,T \qquad (4)$$

Solids extremely disordered, such as glass and labradorite are included neither in Eq. (3) nor in Eq. (4). Such materials exhibit a thermal resistivity modestly decreasing with temperature (e.g. Stevels, 1962; Linvill & Pohl, 1985). Fig. 2 demonstrates the temperature dependence of the thermal resistivity of some common crystalline rock types. The quantities $A_{st}$ and $A_{ph}$ are given in Table 4. It seems that $A_{st}$ is approximately 0.25. The heat conductivity of quartz-bearing rocks is more sensitive to temperature variations ($A_{ph}$ 4 $10^{-4}K^{-1}$) than that of rocks free of quartz ($A_{ph}$ 3 $10^{-4}K^{-1}$). The derivative of Eq. (3) is shown for different rock types in Fig. 3. It decreases from room temperature to 600°C by a factor of 3 with the exception of quartzite of which the thermal properties are much more sensitive to temperature variations.

Some Upper Carboniferous sedimentary rocks of the Ruhr basin/FRG are investigated. The temperature applied did not exceed 200°C. The core samples from two boreholes have a man porosity of 3.8 ± 0.6%. The water-saturated samples were measured up to 100°C by soldering the sample in a copper foil capsule. After correction for the copper cover, the water saturation is found to raise the thermal conductivity of the sedimentary rock by 14 ± 3%. The medium-grained sandstone is not only a better heat conductor than the fine-grained one but also the temperature coefficient of thermal conductivity has a higher value than that of fine-grained samples. The investigated siltstone conducts the heat poorly and exhibits merely a weak, or even no change with temperature (Table 4).

**Table 3** – Thermal conductivity dependence upon contact pressure of some sedimentary rocks of the Ruhr basin/FRG and of some common crystalline rock types with mean values of up to 10 specimens of each rock sample from 10 to 60 MPa.

| sample nº | rock type | $\frac{10^3}{K_0}\frac{\partial K}{\partial p}$ [MPa$^{-1}$] range | mean |
|---|---|---|---|
| 13 | medium-grained sandstone | 2, . . . 9 | 3.4 |
| 14 | fine-grained sandstone | 0 . . . . 3 | 1.4 |
| 15 | siltstone | 1 . . . . 5 | 2 |
| 10, 11, 12 | granite | 1.5 . . . . 2.5 | 2 |
| 8,9 | gabbro | 0 . . . . 0.5 | 0.3 |
| 4,5 | peridodite | 0 . . . . 1.5 | 0.6 |

## DISCUSSION AND APPLICATION

The uniaxial stress or contact pressure dependence of the thermal conductivity has been investigated; contact pressures of up to 60 MPa were applied. If the stress values are converted to depth, they correspond to a maximum depth of 2 km. Since most of the boreholes encounter depths of this range, the results are of some value for heat flow density determination. However, the nonlinear behaviour of the thermal conductivity of sedimentary rocks with stress might yield serious uncertainties within the uppermost 500 m of depth. The in-situ conductivity cannot be estimated from the experiments. If no contact pressure is applied when determining the conductivity, the measured values are too low, in general, and at low contact pressures, the effects of the specimen preparation can determine the measured values so that the in-situ variations cannot be inferred correctly. This means that the results using Eq. (1) can be applied to crystalline rocks from the surface downwards and to sedimentary layers from a depth of about 500 m downwards.

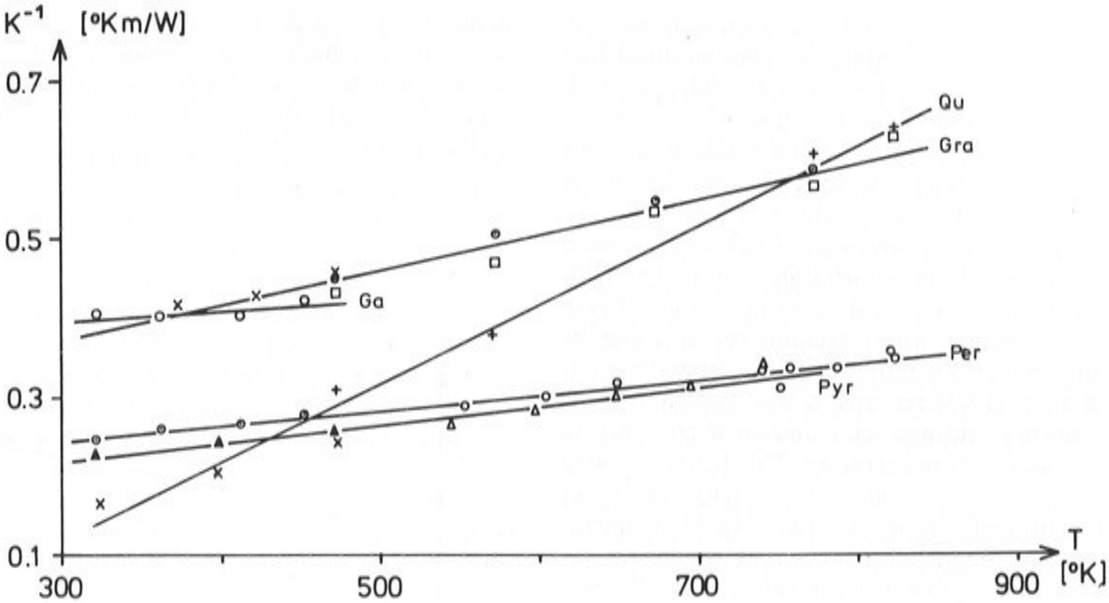

**Figure 2** — Thermal resistivity of some crystalline rock samples in dependence upon temperature at p = 50 MPa. Qu — quartzite (n? 3), Gra — Granite (n? 2), Ga — gabbro (n? 8), Per — peridotite (n? 5), Pyr — pyroxenite (n? 6).

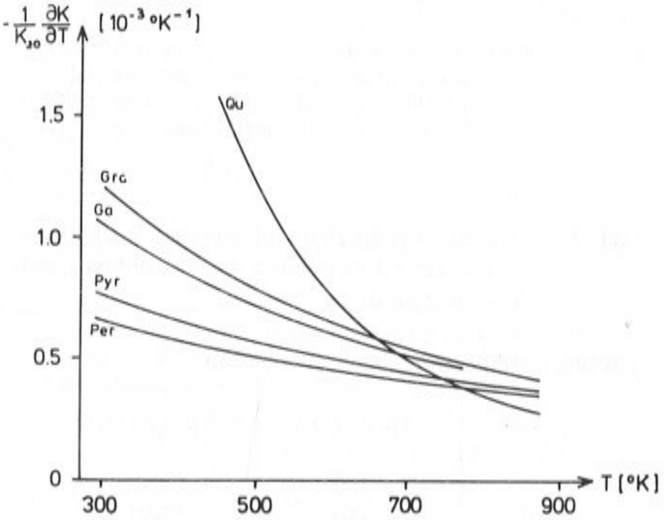

**Figure 3** — Partial derivative of the thermal conductivity with respect to temperature as a function of the temperature for some crystalline rock samples at p = 50 MPa. Qu — quartzite (n? 3), Gra — granite (n? 2), Ga — gabbro after Mirkovich & Soles (1978), Pyr — pyroxenite (n? 6), Per — peridotite (n? 5).

The temperature sensitivy of the heat conduction is described by a hyperbolic function in a temperature range between about 50°C and 600°C. However, Eq. (3) is not entirely valid at the lower temperature. Instead of Eq. (2), a linear law can describe the temperature sensitivity of the thermal conduction up to a temperature of about 200°C sufficiently well.

The constant $A_{st}$ in Eq. (3), resp. B in Eq. (4) comprises structural as well as textural effects, e.g. the effect of porosity and grain size, intragranular lamellar structures, physical or chemical crystal defects and lattice imperfections. From this follows that each rock

**Table 4** — Constants of the temperature dependence of the thermal resistivity according to Eq. (3), resp. Ed. (4) for some crystalline and sedimentary rocks.

| sample n? | rock type | $A_{st}$ [m°K/W] | $A_{ph}$ [$10^{-4}$m/W] |
|---|---|---|---|
| a) | | | |
| 3 | quartzite | −0.135 | 8.85 |
| 2 | granite | 0.234 | 4.52 |
| 1 | qu-diorite | 0.285 | 4.25 |
| | gabbro[1]) | 0.22 | 3.5 |
| 6 | pyroxenite | 0.15 | 2.31 |
| 5 | peridodite | 0.19 | 1.89 |
| b) | | | |
| 10, 11, 12 | granite | 0.14–0.33 | 2.2–4.3 |
| 8,9 | gabbro | 0.21–0.36 | 1.2–3.9 |
| 7 | pyroxenite | 0.26 | 1.05 |
| 4 | olivinite | 0.164 | 2.67 |
| | | B | $A_{ph}$ |
| 13 | medium-grained sandstone | 0.08 | 5.88 |
| 14 | fine-grained sandstone | 0.14 | 5.68 |
| 15 | siltstone | 0.53 | 2.18 |

[1] Data after Mirkovich & Soles (1978)
a) temperature range between 300 and 850°K
b) temperature range between 300 and 470°K

sample has to be characterized by its own properties. If the structural disorder shortens the phonon mean free path and scatters the phonons noticeably, a weak decreasing conductivity can be observed or even in extreme cases a modestly increasing conductivity with temperature. Such behaviour is demonstrated with the most fine-grained siltstone in Table 4. The conductivity of some granite samples and more frequently, of basic rocks, show very little temperature sensitivity. With sedimentary rocks, this may be due to the effect of very small grain sizes, and with crystalline rocks, it may be due to the phonon scattering of the feldspar fraction. Linvill & Pohl (1985) reported a heat conductivity of some plagioclase feldspars with lamellar microstructure which increases with temperature. This behaviour may compensate the decreasing conductivity of other mineral constituents in part so that a weakly temperature dependent conductivity of the rock results.

In multi-component aggregates, the thermal conductivity is determined by concentrations and the distribution of mineral constituents (Birch & Clark, 1940). As reported by other authors (e.g. Sibitt et al., 1978; Schön, 1983), the quartz fraction largely determines the thermal conductivity of granite. The higher the quartz fraction is, the higher is the heat conductivity of granite. Not only quartz plays such a role, but also olivine and pyroxene which are good heat conductors among the rock forming minerals.

The rock samples are exposed to temperatures reaching up to 600°C and the stress applied is relatively low with a few tens of MPa. If thermal cracking occurs during the measurements, this should influence the results seriously and causes an error which lowers the heat conductivity systematically with increasing temperature. However, no strong influence of thermal cracking of samples on the conductivity could be detected in the course of runs with decreasing temperature and repeated measurements on the same crystalline rock samples, if they were not heated above 450°C. Sedimentary rocks were not heated up to temperatures higher than 200°C.

In order to calculate a thermal conductivity for a given depth, Eqs. (1) and (3), resp. (4) are combined to superpose the contact pressure and temperature effects:

$$K = \frac{1 + C\,(p-10)}{A_{st} + A_{ph}\,T} \qquad (5)$$

As an example, a 2000 m deep borehole is considered. The lithostatic pressure of the crust increases linearly with depth and reaches 54 MPa. Within the borehole, however, this pressure is reduced, the water column reaches, in the same depth, a hydrostatic pressure of about 24 MPa. This value is dependent on the density of the drill mud. According to this reduction of pressure, conductivity measurements at the wall of the borehole are lower than the in-situ conductivity. The pressure decrease due to drilling can cause a 10% lower conductivity than the actual conductivity, if Eq. (1) is applied in Fig. 4 to medium-grained sandstone (nº 13). In lower depths of up to 1000 m, the reduction of conductivity is less than 5%. Because the conductivity increases with decreasing temperature, the error is smaller immediately after drill stop than later when the temperature equilibrium is reached.

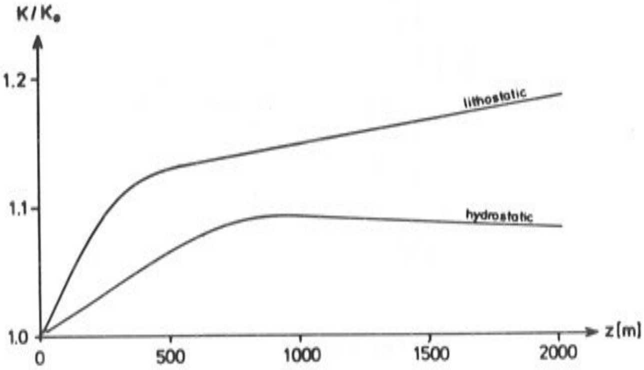

**Figure 4** — Depth variation of the ratio of the conductivity using Eq. 5 and the conductivity at room temperature and zero pressure for lithostatic and hydrostatic pressure applied to medium-grained to medium-grained sandstone (nº 13).

**Table 5** – Thermal conductivity of common rock types under crustal conditions in Precambrian and Phanerozoic areas.

a) assumed temperature-depth distribution

| z (km) | $T_{Prec.}$ (°K) | $T_{Phan.}$ (°K) |
|---|---|---|
| 5 | 360 | 490 |
| 10 | 430 | 640 |
| 15 | 500 | 740 |
| 20 | 570 | 810 |
| 25 | 620 | 870 |
| 30 | 670 | 930 |

b) calculated thermal conductivity K [W/m°K]

| | granite | | gabbro | | ultrabasic rocks | |
|---|---|---|---|---|---|---|
| z (km) | Prec. | Phan. | Prec. | Phan. | Prec. | Phan. |
| 5 | 3.4 | 3.0 | 2.9 | 2.6 | 4.3 | 3.8 |
| 10 | 3.2 | 2.7 | 2.7 | 2.4 | 4.1 | 3.4 |
| 15 | 3.0 | 2.5 | 2.6 | 2.2 | 3.9 | 3.2 |
| 20 | 2.9 | 2.4 | 2.5 | 2.2 | 3.7 | 3.1 |
| 25 | 2.8 | 2.3 | 2.5 | 2.1 | 3.6 | 3.0 |
| 30 | 2.7 | 2.3 | 2.4 | 2.1 | 3.5 | 3.0 |

If the thermal conductivity of cores is measured at room temperature and atmospheric pressure, the error in heat flow determination can reach 18% in a depth of 2000 m and a temperature gradient of 25°C/km. The conductivity is in a depth of 500 m 13% higher than the conductivity of a sample measured at room condition.

Assuming mean temperatures in the Phanerozoic as well as in Shield areas, the conductivity resulting from Eq. (5) of some crystalline rocks is given in Table 5 down to a depth of 30 km.

The pressure effect on the thermal conductivity reported in this paper was applied down to a depth of 5 km. Beneath this depth, a value C of $K^{-1} (\partial K/\partial p)_T = 0.07 \text{ GPa}^{-1}$ (Beck et al., 1978) was applied to all rock types because of the lack of data at high pressure.

The effect of temperature on the thermal conductivity is estimated for three rock types from table 4 with:

$1/K$ [mK/W] = $0.235 + 3.67 \cdot 10^{-4}\ T$ [K] for granitic rocks

$1/K$ [mK/W] = $0.26 + 2.87 \cdot 10^{-4}\ T$ [K] for gabbroic rocks

$1/k$ [mK/W] = $0.168 + 2.29 \cdot 10^{-4}\ T$ [K] for ultrabasic rocks.

The lower temperature gradient in Precambrian areas causes a higher thermal conductivity than in Phanerozoic areas. The difference is about 10% at 5 km depth and increases slightly with depth.

From these few data, it can be concluded that a high diversity of thermal properties of common rocks exists within the upper crust and that the range of the variations is reduced to values of about 2 to 2.5 W/mK at the base of the lower crust. The distribution of low conducting feldspar seems to have a bearing on the diversity of temperature distributions within the crust.

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