Measurements of rock thermal conductivity with a Transient Divided Bar
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Abstract

We implemented an apparatus (Transient Divided Bar – TDB) to determine thermal conductivity of rocks. TDB consists of a stack of elements that comprise a rock specimen placed between two copper blocks of cylindrical shape with known thermal capacity. The stack of elements is initially kept at room temperature. The lower block is then cooled, and temperature changes of the upper and lower blocks are continuously recorded. The rate at which heat leaves the upper block depends on the rock thermal conductivity, which is evaluated from the measured temperatures as a function of time. First, TDB was calibrated with silica glass and quartz; then thermal conductivity of specimens of several rock types was measured both with this apparatus and a commercial device. Substantial agreement was obtained between the two apparatuses. An empirical formula was also found for the calculation of the thermal conductivity by using only records of the upper block temperature as a function of time and room temperature. Finally, we present results of thermal conductivity and its relation with porosity and density for a wide set of fine-grained, macroscopically isotropic and homogeneous rocks.

Highlights
Implementation of an apparatus for measuring thermal conductivity
Comparison of results obtained with different devices
Experimental determinations of thermal conductivity of rocks

Keywords
Transient Divided Bar apparatus
Thermal conductivity measurement
Rock porosity and density
1. Introduction

Methods for measuring thermal conductivity of soil and rocks may be generally classified into steady state and transient types. They both may give absolute or relative values, compared to some standards, but in practice the steady–state methods are used in the comparative mode, whereas the transient methods in the absolute mode. Normally, the transient methods can give thermal diffusivity, however, under certain experimental conditions, they can measure directly thermal conductivity (see e.g. Tye, 1969; Parrott and Stuckes, 1975; Beck, 1988, for a review).

Steady–state measurements on rocks are usually made by means of the divided–bar method, first described by Benfield (1939) and Bullard (1939). There are various versions of this device, depending on the temperature and pressure adopted during experiments, as well as the rock specimen size (Birch, 1950; Beck and Beck, 1958; Sass et al., 1971; Blackwell and Spafford, 1987). Rock specimen is placed between bars of known thermal conductivity. The setup is usually vertical, with the specimen between the hot bars at the top and the cold bars at the bottom; the heat transfer downwards prevents any convection within the specimen. Measurements are taken when a steady heat-state flow occurs along the bars.

The most commonly used method for soft rocks is the needle probe, described by De Vries and Peck (1958) and by Von Herzen and Maxwell (1959). It is based on the theory of an infinite line heat source, embedded within an infinite medium. The apparatus is designed such that the heat source and sensor are both located within the probe. For hard rocks, measurements under transient conditions are usually made by means of a plane or a circular heat source, with a temperature sensor at the centre (Beardsmore and Cull, 2001).

The availability of electronic tools for data acquisition allowed the improvement of some classical methods, such as the line source (see Pribnow and Sass, 1995, for a review) and the
pulsed line source (Lewis et al., 1993). A further implementation of electronic data acquisition is the scanning of rock specimen surfaces with a focused, mobile and continuously operated, constant heat source, in combination with a temperature sensor (Popov, 1983; Popov et al., 1999). In this paper, we deal with an apparatus (Transient Divided Bar – TDB), implemented through several years of trial investigations on crystalline and sedimentary rocks (Pasquale, 1983; Pasquale et al., 1988 and 2011). The basic principles of the method are described. A comparison of the thermal conductivity results obtained with TDB and a commercial device is then carried out. Finally, we present a synthesis of several measurements and discuss the results in relation to porosity and density of a wide set of rocks.

2. Apparatus

The Transient Divided Bar (TDB) is based on the method by Joffe (1956) for determining thermal conductivity of semiconductors. Figure 1 shows a sketch of this apparatus. A cylindrical specimen of rock is interposed between two cylindrical blocks of copper of known thermal capacity. The upper block has the same diameter of the specimen and acts as a heat source, whereas the lower block, more massive, works as a heat sink. The heat flowing through the specimen is equal to the heat absorbed by the sink, so that the thermal conductivity can be found if the temperature changes of the source and the sink are measured.

The experiment begins when the stack of elements attains the room temperature $T_o$. The lower block is then cooled by immersing it into a thermostatic bath at temperature generally 10–15 °C lower than $T_o$. After little time, this yields a uniform temperature gradient $(T_u-T_l)/h$, where $T_u$ and $T_l$ are the temperatures of the upper and lower blocks, respectively, measured as close as possible to the specimen, and $h$ is the thickness of the specimen. Temperatures are recorded by means of thermocouples connected to a digital acquisition system.
On the base of the Fourier's postulate, the amount of heat removed from the upper block, in a given time step $\Delta t$, is given by

$$\frac{k'S}{h} \int_{t_i}^{t_2} (T_u - T_l) \, dt = \frac{k'S}{h} (\bar{T}_u - \bar{T}_l) \Delta t$$

(1)

where $k'$ is the thermal conductivity of the rock specimen, $h$ and $S$ are the height and cross-sectional area of the specimen, and $(\bar{T}_u - \bar{T}_l)$ is the difference between the average values of $T_u$ and $T_l$ during $\Delta t = t_2 - t_1$. From equation (1), we obtain

$$k' = \frac{C_u \Delta T_u \, h}{S (\bar{T}_u - \bar{T}_l) \Delta t}$$

(2)

where $C_u$ is the thermal capacity at constant pressure of the upper block and $\Delta T_u$ is the variation of $T_u$ during a time step $\Delta t$.

2.1. Corrections and experimental errors

Two corrections must be applied as additional thermal processes can be present while measuring. The former has to do with the heat coming from the rock specimen, the latter with the heat transfer from the surrounding environment to the upper block.

The heat flowing from the specimen can be taken into account by considering an effective thermal capacity $C_{eff}$. Detailed theoretical analyses by Kaganov (1958), Swann (1959) and Drabble and Goldsmith (1961) showed that $C_{eff}$ is given by the sum of $C_u$ and one third of the specimen thermal capacity. These analyses also suggested that the correction for the heat from the environment can be estimated by operating under steady-state conditions, i.e. when the temperatures $T_u$ and $T_l$ are constant. This occurs about two hours after the experiment begins. The upper block absorbs heat from the environment, whose temperature $T_o$ is kept constant during the measurement. The heat $Q_s$ transmitted from the upper block, at constant temperature $T_{us}$, to the lower block, at constant temperature $T_{ls}$, will be equal to
\[ Q_s = F(T_o - T_{sw}) = \frac{k'(T_{sw} - T_o)S \Delta t}{h} \]  

from which we can calculate the quantity \( F \). During the experiment, the relation

\[ Q = F(T_o - \bar{T}_u) \]

holds, which allows the calculation for each \( \bar{T}_u \) of the amount of heat coming from the environment. By taking into account the effective thermal capacity and the heat from the environment, the corrected conductivity value \( k \) is then given by

\[ k = \frac{C_{eff} \Delta T_u + F(T_o - \bar{T}_u)h}{(\bar{T}_u - \bar{T})S \Delta t} \]

Possible heat transfer by convection within the specimen is unlikely because, similarly to the divided bar method, the lower block is kept at a lower temperature. The upper block and specimen are housed in order to minimize air current effects on the surrounding environment temperature.

A significant error when measuring thermal conductivity may derive from the difficulty in obtaining an ideal thermal contact between the blocks and the rock specimen, in particular if porosity is large. Particular care should be taken in the preparation of the specimen base surfaces, making them flat to within 0.1 mm (no wedge shape), smoothed and mutually parallel to within 0.03 mm throughout (no dome or concavity on the specimen surface). A film of silicone paste smeared on the contact surfaces and a light pressure (about 2.0 bar) exerted on the upper block improve the contact. The thermal contact resistance of this very thin film (0.01 mm) of silicon is equivalent to that given by a rock sheet of a few hundredths of millimetre. Such a resistance, for \( h=1.6 \) cm, as usually adopted for the specimen height, is lower than 2% of the total thermal contact resistance of the rock specimen.

With regard to the time interval over which measurements can be made and a reasonable accuracy achieved, if the lateral heat loss is neglected, the temperature data should be reliable when recorded within the limits of the following inequality (Kaganov, 1958)
\[
\frac{\ln 2 h^2}{\pi^2 \chi} << t \leq \frac{C_s h^2}{C_r \chi}
\]

where \( \chi \) is the thermal diffusivity and \( C_r \) the thermal capacity of the rock specimen. The order of magnitude of \( t \) is a few minutes.

Joffe and Joffe (1958) reported that the experimental error of this method was less than 5% and the reproducibility is about 2%, for \( k \) ranging from 1 to 10 W m\(^{-1}\)K\(^{-1}\). The best performances were obtained when the specimen radius is equal to that of upper block. This condition has always been fulfilled in our experiments. The specimen height matters only if the radius is smaller than the optimal one. We checked the performances of our apparatus by means of a series of measurements on silica glass and crystalline quartz specimens. The comparison of thermal conductivity results with data compiled by various authors (Table 1) shows differences of less than 5%, which indicate that TDB has fairly good accuracy and experimental error consistent with that reported by Joffe and Joffe (1958). Variations from 1.5 to 2.5 bar of the pressure exerted on the upper block to improve the thermal contact between the blocks and the rock specimen do not imply any significant effect.

2.2. Measurement procedure

Figure 2 gives an example of temperature curves recorded with TDB during a test on a sample of dolomite. A cylindrical specimen was obtained by means of a diamond head corer of radius 0.85 cm, i.e. equal to that of the upper block. Both bases of the specimen were rubbed down by using fine abrasives to get flat, parallel and smooth surfaces. The final height of the cylindrical specimen was 1.6 cm.

A specific heat of 382 J kg\(^{-1}\) K\(^{-1}\) was assumed for the blocks of copper (Baehr and Stephan, 1998). The specific heat of the rock (930 J kg\(^{-1}\) K\(^{-1}\)) was measured with a 3% uncertainty by means of a water calorimeter in the temperature range from 25 \(^\circ\)C (final equilibrium temperature...
of the rock plus the calorimetric fluid) and 100 °C (initial temperature of the rock). For this measurement, the amount of water that the rock absorbs during immersion and the heat exchange between calorimeter and environment was taken into account.

The temperature $T_u$ and the difference $T_u - T_l$ have been recorded for 300 s. The time interval between 150 and 270 s, which is considered for the thermal conductivity inference, is well within the theoretical range (20–780 s), given by Eq. (6) for a typical thermal diffusivity value of the order of $10^{-6}$ m$^2$ s$^{-1}$. Twelve thermal conductivity determinations were carried out at time steps $\Delta t$ of 10 s. The test was carried out at normal pressure and temperature ($T_o=24.8$ °C). The temperature of the thermostatic bath was 10 °C and the value of $F$ at steady–state conditions was 0.64 J K$^{-1}$. Table 2 lists temperatures and thermal conductivity values determined from Eq. (5) at each time step. The average of all the determinations (4.11±0.07 W m$^{-1}$ K$^{-1}$) was taken as the final value of thermal conductivity.

3. Comparative experiments

A comparative study was carried out by measuring thermal conductivity of several specimens with TDB and the commercial device ISOMET (Applied Precision Ltd., Slovak Republic). The latter is equipped with various surface probes and the measurement is based on the analysis of the time dependence of the specimen thermal response to heat–flow impulses. Integration of the temperature time curve is carried out during both the heating and cooling cycle. The heat flow impulses are induced by an electrical resistance heater enclosed in the probe, which is in a direct contact with the specimen. The error of measurement and the reproducibility claimed by the manufacturer are of the order of 5% and 3%, respectively.

The comparative study was carried out on samples of borosilicate glass and various rock types, fine-grained and macroscopically homogeneous and isotropic. For each sample, we tested two specimens, one with a flat surface, suitable to perform measurements with ISOMET, and another
of cylindrical shape for the measurements with TDB. The specific heat of the rocks varies little and the specimen heat capacity \( C_s \) is much smaller than that of the copper blocks. Therefore, we estimated \( C_s \) with adequate approximation by multiplying the specimen mass for a constant value of specific heat of 900 J kg\(^{-1}\) K\(^{-1}\).

The list of materials used together with the obtained results is shown in Table 3. There is substantial agreement between the two series of results; the values obtained with TDB are slightly larger (on average 2.6%). Small differences can be ascribed to the difficulty in obtaining optimal thermal contact with the specimens under test. A maximum deviation of about 0.3 W m\(^{-1}\)K\(^{-1}\) (10%) was obtained for a phyllite sample.

Figure 3 depicts the temperature ratio \( \theta = T_u/T_o \) as a function of time for all the tested specimens. It turns out that the decrease of this ratio with time is faster for the specimens with larger thermal conductivity. This makes possible the determination of \( k \) by means of an empirical relation between \( \theta \) and \( k \). Figure 4 shows \( \theta \) against \( k \) at two different times \( t \) after the experiment begins. For \( t=180 \) s the curve which best fits data is

\[
k = 39.2 - 56.9 \theta_{180} + 17.7 \theta^2_{180}
\]  

(7)

whereas for \( t=240 \) s

\[
k = 28.2 - 42.6 \theta_{240} + 14.5 \theta^2_{240}
\]  

(8)

Equations (7) and (8) are applicable for \( 0.8 < \theta_{180} < 1.0 \) and \( 0.7 < \theta_{240} < 1.0 \), respectively, and hold for rock specimens of radius 0.85 cm and high 1.6 cm.

4. Applications

After testing the performances of TDB, a series of measurement was carried on a number of water-saturated sedimentary and crystalline rocks. Tables 4 and 5 summarize the results obtained for specimens together with density and, only for sedimentary rocks, porosity. Mass was measured using a high precision balance and the specimen volume, \( V \), was determined by means of immersion in water. The pore volume of argillaceous and evaporitic rocks was inferred by
means of a helium pycnometer. For porosity calculations of the other sedimentary rocks, specimens were oven-dried for one day at 70°C to determine the dry weight, $W_d$, and water saturated to determine the wet weight, $W_w$. Porosity, $\phi$, is then defined as

$$\phi = 1 - \frac{(W_d - W_w)}{V}$$

(9)

Mass change between the dehydrated and water–saturated states was accounted for by the influx of water into the pore spaces. After cooling to room temperature, the dry specimens were saturated by simply immersing them in water for two days.

The sedimentary rock specimens (Table 4) were recovered from petroleum exploration wells, scattered in the Po Basin (Northern Italy). They form a broad collection of the basin main lithologies up to about seven kilometer depth (see Pasquale et al., 2011, for a detailed description of lithotypes). Most of the samples are clastic and consist of framework silicates and carbonate grains in an argillaceous matrix or calcareous cement. Marls and silty marls of marine origin prevail and are formed by calcium carbonate mud, containing variable amount of clays. The argillaceous sandstone samples are lithic and feldspatic arenites, primarily composed by cemented sandy sediment, in many cases dominated by sand–sized rock fragments and quartz. Chemical/biochemical sediments include carbonatic, evaporitic (anhydrite) and siliceous (radiolarite) rocks.

The thermal conductivity ranges from 2.2 to 4.6 W m$^{-1}$ K$^{-1}$. The minimum value corresponds to calcareous marl and the maximum to dolostone (Table 4). Besides dolostones, larger values of conductivity characterize anhydrites, whereas lower conductivity is typical of calcareous marls. Carbonate rocks and argillaceous sandstones show intermediate values. Porosity and density values are also listed in Table 4, while Fig. 5 shows their relation with thermal conductivity. The porosity varies from about 3% (radiolarite, mudstone and anhydrite) to 30% (calcarenite and calcareous marl).

All the investigated crystalline rocks samples were collected by avoiding major fractures that make coring difficult (Table 5). The rocks belong to plutonic and ophiolitic associations of
northern Italy. The samples are all of low porosity (maximum 1.5%) and their petrographic descriptions are given by Pasquale et al. (1988 and 2001). Plutonic rocks are mostly granitoid with composition ranging from granitic to tonalitic. Ophiolite rock are mainly peridotites of lherzolitic and harzburgitic type, more or less affected by serpentinization processes, and, to a smaller extent, of dunite type almost exclusively constituted by olivine. The measured thermal conductivity and density, and the content of the rock-forming minerals which most affect such parameters are listed in Table 5. The thermal conductivity values range from 1.8 to 4.1 W m⁻¹ K⁻¹. Figure 6 depicts thermal conductivity as a function of density for rocks of sialic-intermediate and ultrabasic composition.

5. Discussion and conclusions

Knowledge of rock thermal properties is of basic interest not only in geothermal studies, but also in oil and gas industry. To this regard, laboratory measurements of thermal conductivity, coupled with other petrophysical properties, can give a valuable contribution. We implemented a laboratory apparatus for measurements of rock thermal conductivity that has the advantage of requiring short measurement times. Moreover, it gives a final value of thermal conductivity as a result of multiple determinations on the same specimen, thus strengthening the reliability of the measurement. The thermal conductivity of a wide spectrum of water-saturated rocks was investigated with this apparatus.

For the sedimentary rocks, a wide variability in thermal conductivity was found. In order to analyze such variability, we also determined porosity and density. There may be wide variation of these parameters, which may yield large differences in thermal properties. The thermal conductivity decreases with the increase of porosity, whereas density shows an opposite trend (Fig. 5). Differences in composition can also contribute to thermal conductivity variation, but in the analyzed rock porosity is so large that it plays a major role. Moreover, it should be noted that the porosity estimate could be biased as the rocks were saturated at room pressure and the
presence of isolated pores was of course neglected. Therefore, a comparison of our thermal conductivity results with earlier compilations is difficult.

The thermal conductivity results of crystalline rocks are generally consistent with literature data (e.g. Birch, 1942; Clark, 1966; Desai et al., 1974, Kappelmeyer and Häenel, 1974; Roy et al. 1981; Čermák and Rybach, 1982, Robertson, 1988; Zoth and Haenel 1988; Clauser and Huenges 1995), because their porosity is very low and consequently the thermal properties are mainly dependent upon the mineralogical composition. The obtained dataset may integrate earlier compilations.

As suggested by Beck (1965), for accurate determinations of thermal conductivity the ratio between the minimum thickness of the specimen and the grain size must be larger than 15. This condition was always fulfilled only in the sedimentary specimens. Therefore, a large standard deviation on the average value of thermal conductivity of some crystalline rocks (granite, granodiorite, lherzolite) can be ascribed to a large grain size. The presence of cracks in the specimens can further affect the results. Walsh and Decker (1966) argued that thermal conductivity of low-porosity rocks may differ appreciably from that of the matrix only for dry rocks and containing pore in the shape of cracks. Thus, we carried out measurements on water-saturated rocks.

For whole dataset of the crystalline rocks, a clear relation between thermal conductivity and density cannot observed. However, if we distinguish the two subsets, sialic-intermediate and ultrabasic composition, we find that in the former the thermal conductivity decreases and in the latter increases with the increase of density (Fig. 6). In the sialic-intermediate rocks, the decrease from granite to gabbro is due to reduction of quartz content associated with the increase of hornblende (Table 5). Quartz has high conductivity (7.7 W m⁻¹K⁻¹) and low density (2650 kg m⁻³), whereas hornblende is characterized by low conductivity (2.81 W m⁻¹K⁻¹) and high density (3150 kg m⁻³). For ultrabasic rocks, the increase with density can be accounted for by the olivine content. This mineral has high density (3300 kg m⁻³) and conductivity (4.00 W m⁻¹ K⁻¹).
Anorthosite does not contain olivine and is characterized by the lowest values of density and thermal conductivity. This is caused by plagioclase which is main rock-forming mineral and presents low conductivity (1.97 W m\(^{-1}\) K\(^{-1}\)) and density (2650 kg m\(^{-3}\)) values.

In summary, the implemented apparatus allow reliable and fast thermal conductivity assessments of fine-grained rocks. With minor modifications the same apparatus could be used for high temperature thermal conductivity measurements. Small diameter rock specimens used in this study pose some challenges that occur above all in crystalline rocks, often presenting large mineral grains. Future evaluations will include thermal conductivity measurement on specimen of large size and the evaluation of the contact thermal resistance in rocks with large porosity.

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**References**


Figure captions

Fig. 1. a) Diagram of TDB used for laboratory thermal conductivity determination. b) Typical $T_u$ and $T_u-T_l$ curves recorded during the experiment.

Fig. 2. $T_u$ and $T_u-T_l$ curves vs. time for specimen of dolomite (radius 0.85 cm, height 1.6 cm). Twelve thermal conductivity values at time steps $\Delta t =10$ s were determined in 150–270 s time range (see Table 2).

Fig. 3. Temperature ratio $\vartheta=T_u/T_o$ vs. time $t$ for materials in Table 3.

Fig. 4. Temperature ratio $\vartheta=T_u/T_o$ vs. thermal conductivity $k$ for time $t$ of 180 and 270 s. The curve parameter is time (see text).

Fig. 5. Thermal conductivity vs porosity and density for the sedimentary rocks of Table 4.

Fig. 6. Thermal conductivity vs density for crystalline rocks of Table 5. (a) Sialic-intermediate rocks: 1 – Granite, 2 – Granodiorite, 3 – Tonalite, 4 – Syenite, 5 – Diorite, 6 – Gabbro, (b) Ultrabasic rocks: 7 – Anorthosite, 8 – Hornblendite, 9 – Lherzolite, 10 – Harzburgite, 11 – Dunite.
Table 1
Comparison of thermal conductivity (in W m\(^{-1}\)K\(^{-1}\)) at room temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Present study</th>
<th>Reference study</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica glass</td>
<td>1.36</td>
<td>1.38(^{a}), 1.31(^{b})</td>
<td>-1.5 - 3.8 %</td>
</tr>
<tr>
<td>Crystalline quartz ((\perp))</td>
<td>6.08</td>
<td>6.15(^{a})</td>
<td>-1.1 %</td>
</tr>
<tr>
<td>Crystalline quartz ((\parallel))</td>
<td>10.66</td>
<td>10.43(^{a}), 10.17(^{c})</td>
<td>2.2 - 4.8 %</td>
</tr>
</tbody>
</table>

\(^{a}\)Ratcliffe (1959), \(^{b}\)Horai and Simmons (1969), \(^{c}\)Birch and Clark (1940).

Table 2
Temperatures \(T_{ni}, \Delta T_{ni}, T_{fi}\) recorded during the experiment and results of thermal conductivity \(k\) for dolomite specimen. Twelve time steps were investigated: \(t_i\) and \(t_f\) are the initial and final time of each step (see text).

<table>
<thead>
<tr>
<th>Time step</th>
<th>(t_i) (s)</th>
<th>(t_f) (s)</th>
<th>(T_{ni}) (°C)</th>
<th>(\Delta T_{ni}) (°C)</th>
<th>(T_{fi}) (°C)</th>
<th>(k) (W m(^{-1})K(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>160</td>
<td>21.61</td>
<td>0.253</td>
<td>7.79</td>
<td>3.99</td>
</tr>
<tr>
<td>2</td>
<td>160</td>
<td>170</td>
<td>21.30</td>
<td>0.252</td>
<td>7.67</td>
<td>4.06</td>
</tr>
<tr>
<td>3</td>
<td>170</td>
<td>180</td>
<td>20.98</td>
<td>0.250</td>
<td>7.56</td>
<td>4.12</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
<td>190</td>
<td>20.67</td>
<td>0.246</td>
<td>7.44</td>
<td>4.14</td>
</tr>
<tr>
<td>5</td>
<td>190</td>
<td>200</td>
<td>20.37</td>
<td>0.243</td>
<td>7.32</td>
<td>4.18</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>210</td>
<td>20.07</td>
<td>0.238</td>
<td>7.19</td>
<td>4.18</td>
</tr>
<tr>
<td>7</td>
<td>210</td>
<td>220</td>
<td>19.77</td>
<td>0.233</td>
<td>7.04</td>
<td>4.18</td>
</tr>
<tr>
<td>8</td>
<td>220</td>
<td>230</td>
<td>19.48</td>
<td>0.228</td>
<td>6.87</td>
<td>4.16</td>
</tr>
<tr>
<td>9</td>
<td>230</td>
<td>240</td>
<td>19.20</td>
<td>0.223</td>
<td>6.68</td>
<td>4.14</td>
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<tr>
<td>10</td>
<td>240</td>
<td>250</td>
<td>18.93</td>
<td>0.217</td>
<td>6.47</td>
<td>4.08</td>
</tr>
<tr>
<td>11</td>
<td>250</td>
<td>260</td>
<td>18.66</td>
<td>0.212</td>
<td>6.25</td>
<td>4.04</td>
</tr>
<tr>
<td>12</td>
<td>260</td>
<td>270</td>
<td>18.40</td>
<td>0.207</td>
<td>6.01</td>
<td>3.99</td>
</tr>
</tbody>
</table>

Mean 4.11
Dev. stand. 0.07

Table 3
Comparison of thermal conductivity determinations: \(k\), our apparatus: \(k_{ISO}\), ISOMET device. Percentage differences between the two values \(\Delta k\) are given.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg m(^{-3}))</th>
<th>(k) (W m(^{-1})K(^{-1}))</th>
<th>(k_{ISO}) (W m(^{-1})K(^{-1}))</th>
<th>(\Delta k) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Borosilicate glass</td>
<td>2230</td>
<td>1.07</td>
<td>1.03</td>
<td>3.9</td>
</tr>
<tr>
<td>2 – Gypsum</td>
<td>2486</td>
<td>1.71</td>
<td>1.68</td>
<td>1.8</td>
</tr>
<tr>
<td>3 – Limestone</td>
<td>2593</td>
<td>2.57</td>
<td>2.48</td>
<td>3.6</td>
</tr>
<tr>
<td>4 – Phyllite</td>
<td>2764</td>
<td>3.20</td>
<td>2.91</td>
<td>10.0</td>
</tr>
<tr>
<td>5 – Dolomite</td>
<td>2838</td>
<td>4.11</td>
<td>4.23</td>
<td>-2.8</td>
</tr>
<tr>
<td>6 – Anhydrite</td>
<td>2813</td>
<td>4.60</td>
<td>4.65</td>
<td>-1.1</td>
</tr>
</tbody>
</table>
### Table 4
Bulk thermal conductivity $k$ (water–saturated), porosity and dry density of isotropic sedimentary rocks. Standard deviation in brackets. $N$ is number of specimens.

<table>
<thead>
<tr>
<th>Rock</th>
<th>Lithotype</th>
<th>$N$</th>
<th>$k$ (W m$^{-1}$ K$^{-1}$)</th>
<th>Porosity (%)</th>
<th>Density (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>range</td>
<td>mean</td>
<td>range</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clastic</td>
<td>Marl</td>
<td>19</td>
<td>2.15–3.08</td>
<td>2.77 (0.23)</td>
<td>6.0–37.0</td>
</tr>
<tr>
<td></td>
<td>Silty marl</td>
<td>18</td>
<td>2.85–3.66</td>
<td>3.16 (0.26)</td>
<td>2.0–20.0</td>
</tr>
<tr>
<td></td>
<td>Calcareous marl</td>
<td>6</td>
<td>1.99–2.37</td>
<td>2.17 (0.13)</td>
<td>22.0–35.0</td>
</tr>
<tr>
<td></td>
<td>Argillaceous limestone</td>
<td>3</td>
<td>3.58–3.63</td>
<td>3.60 (0.03)</td>
<td>7.5–12.0</td>
</tr>
<tr>
<td></td>
<td>Argillaceous sandstone</td>
<td>6</td>
<td>2.60–3.40</td>
<td>3.00 (0.29)</td>
<td>8.0–25.0</td>
</tr>
<tr>
<td></td>
<td>Calcarenite</td>
<td>3</td>
<td>2.18–2.50</td>
<td>2.34 (0.16)</td>
<td>25.0–32.0</td>
</tr>
<tr>
<td>Chemical–biochemical</td>
<td>Mudstone</td>
<td>5</td>
<td>3.04–3.48</td>
<td>3.30 (0.16)</td>
<td>0.5–6.0</td>
</tr>
<tr>
<td></td>
<td>Wackestone</td>
<td>5</td>
<td>3.10–3.20</td>
<td>3.16 (0.04)</td>
<td>3.0–10.0</td>
</tr>
<tr>
<td></td>
<td>Packstone</td>
<td>4</td>
<td>3.00–3.45</td>
<td>3.23 (0.18)</td>
<td>3.0–6.0</td>
</tr>
<tr>
<td></td>
<td>Grainstone</td>
<td>5</td>
<td>2.95–3.36</td>
<td>3.12 (0.16)</td>
<td>6.5–12.0</td>
</tr>
<tr>
<td></td>
<td>Dolostone</td>
<td>5</td>
<td>4.25–4.45</td>
<td>4.60 (0.49)</td>
<td>1.5–7.5</td>
</tr>
<tr>
<td>Siliceous</td>
<td>Radiolarite</td>
<td>4</td>
<td>3.16–3.46</td>
<td>3.37 (0.14)</td>
<td>0.5–5.5</td>
</tr>
<tr>
<td>Evaporitic</td>
<td>Anhydrite</td>
<td>5</td>
<td>3.15–3.65</td>
<td>3.39 (0.22)</td>
<td>0.5–5.0</td>
</tr>
</tbody>
</table>

### Table 5
Thermal conductivity $k$ and density of crystalline rocks, and content of minerals (Qtz – quartz, Hbl – hornblende, Ol – olivine (Fa$_{10}$)) which most affect such parameters. Standard deviation in brackets. $N$ is number of specimens.

<table>
<thead>
<tr>
<th>Lithotype</th>
<th>$N$</th>
<th>$k$ (W m$^{-1}$ K$^{-1}$)</th>
<th>Density (kg m$^{-3}$)</th>
<th>Mineral (in vol. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>range</td>
<td>mean</td>
<td>range</td>
</tr>
<tr>
<td>1 – Granite</td>
<td>22</td>
<td>2.44–3.49</td>
<td>2.88 (0.26)</td>
<td>2620 (20)</td>
</tr>
<tr>
<td>2 – Granodiorite</td>
<td>16</td>
<td>2.24–3.03</td>
<td>2.52 (0.24)</td>
<td>2690 (40)</td>
</tr>
<tr>
<td>3 – Tonolite</td>
<td>10</td>
<td>2.06–2.25</td>
<td>2.16 (0.07)</td>
<td>2720 (20)</td>
</tr>
<tr>
<td>4 – Syenite</td>
<td>3</td>
<td>2.19–2.34</td>
<td>2.25 (0.08)</td>
<td>2720 (40)</td>
</tr>
<tr>
<td>5 – Diorete</td>
<td>14</td>
<td>1.73–2.07</td>
<td>1.89 (0.11)</td>
<td>2840 (60)</td>
</tr>
<tr>
<td>6 – Gabbro</td>
<td>12</td>
<td>1.65–2.29</td>
<td>1.94 (0.19)</td>
<td>2940 (80)</td>
</tr>
<tr>
<td>7 – Anorthosite</td>
<td>4</td>
<td>1.67–1.83</td>
<td>1.76 (0.07)</td>
<td>2730 (60)</td>
</tr>
<tr>
<td>8 – Hornblendite</td>
<td>5</td>
<td>2.57–2.79</td>
<td>2.71 (0.08)</td>
<td>3130 (70)</td>
</tr>
<tr>
<td>9 – Lherzolite</td>
<td>11</td>
<td>3.31–4.00</td>
<td>3.70 (0.25)</td>
<td>3110 (50)</td>
</tr>
<tr>
<td>10 – Harzburgite</td>
<td>3</td>
<td>3.52–3.66</td>
<td>3.60 (0.07)</td>
<td>3090 (20)</td>
</tr>
<tr>
<td>11 – Dunite</td>
<td>3</td>
<td>4.04–4.16</td>
<td>4.11 (0.06)</td>
<td>3340 (20)</td>
</tr>
</tbody>
</table>
Figure 1

(a) Schematic diagram of the experimental setup.

(b) Graph showing temperature changes over time.

Figure 2

Graph illustrating temperature differences over time.
Figure 3

Fig. 4
Fig. 5

Fig. 6