

Appendix 1

Thermal conductivity in rocks: methods and natural variation

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A literature review submitted in partial fulfilment of the requirement of a Bachelor of Science with Honours.

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Abstract

The thermal conductivities of rocks are used in geothermal exploration to build heat flow models. The two most commonly used methods to determine this parameter are the needle probe, which relies on a transient thermal field, and the divided bar, relying on a steady thermal field that is generated between two plates. Standards of reporting thermal conductivity and consistency of results are slowly coming together in the geothermal field. Thermal conductivity results for granites (1.88-3.5W/mK) and siltstones (1.78-3.2W/mK) are consistent with small variation. Sandstones have a greater variation in thermal conductivity due to differing quartz contents between localities. Results for sandstones range from 1.03 W/mK to as high as 7.1W/mK. The divided bar is more appropriate for consolidated samples whereas the needle probe should be used for soft sediments and in situ measurements.

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1. Introduction

1.1 *The application of thermal conductivity measurements to geothermal research*

Most research into the thermal properties of rocks for geothermal exploration is currently being undertaken by government and university projects across Australia. In the mineral resources industry thermal properties measurements are predominantly used in petroleum exploration (Beardsmore & Cull 2001; Correia & Jones 1996; Matthews & Beardsmore 2007). New applications in heat flow modelling involve nuclear waste disposal impact modelling and geothermal exploration (Gunn et al. 2005). Geothermal exploration may be broken up into shallow volcanic systems and deep geothermal thermal systems. My thesis project will be focussing on deep geothermal exploration.

Current geothermal exploration methods for deep hot rocks involve drilling suspected hot targets such as granites. Drilling and thermal well logging data helps to build heat flow models of the surrounding area (Hartmann et al. 2007). They help to pick out areas of the crust with high heat flow and potential drilling targets (Matthews & Beardsmore 2007). Heat flow models require measurement of two particular thermal properties: thermal gradient and thermal conductivity (Abdulagatov et al. 2006; Middleton 1993). Thermal gradients are taken *in situ* by thermal well logging and generally over the entire length of the hole (Beardsmore & Cull 2001). Thermal conductivity is usually measured on drill core in a lab, typically by one of two ways, the steady state method or the transient method. Thermal conductivity may also be measured indirectly in the field by the transient method. This report will mainly focus on the most common empirical methods for determining thermal conductivity but will also briefly look at other less used methods.

The scale of the heat flow model depends upon the amount of data collected and the extent of coverage for an area (Matthews & Beardsmore 2007). Country-wide heat flow models are being constructed for Australia, but measurements of thermal gradients and thermal conductivities are clustered in small areas due to circumstances that create deep sampling opportunities, such as mineral exploration. The problem with this is that it results in only a few locations having enough data to create accurate heat flow models, separated by poorly modelled regions (Hartmann et al. 2007; Middleton 1993). Model accuracy is vital to avoid explorers wasting valuable time

and money drilling in the wrong areas (Hartmann et al. 2007). Possible solutions to this problem are (1) collecting more data to improve the resolution of models; or (2) define values for untested lithologies which are then extrapolated to other locations of similar geology in an iterative process that involves comparison of derived models to existing data (Beardsmore & Cull 2001; Förster et al. 2007; Matthews & Beardsmore 2007).

In terms of both measured and assigned parameters little consensus on definitive thermal conductivity responses for certain lithologies. For instance igneous samples have the most consistent results, perhaps due to their more homogeneous and competent nature. Sedimentary rocks have a more heterogeneous and anisotropic nature, and this is expressed as a large range of values (Clauser & Huenges 1995; Midttymme & Roaldset 1999). They may also be less competent and prone to breaking up during testing (Midttymme & Roaldset 1999).

To address this issue the field is in a phase of enhanced data collection of rock thermal properties with the aim of creating a comprehensive database for use around the world (Abdulagatov et al. 2006; Middleton 1993; Midttymme & Roaldset 1999).

Aims and scope of literature review

- **To detail methods for determining the thermal conductivity of rocks.**
- **To describe the advantages and disadvantages of steady state and transient methods.**
- **To examine factors that influence thermal conductivity.**
- **To compile a list of results for each common lithology.**
- **Thermal data is predominantly published in physics, chemistry, geotechnical and engineering journals.**
- **Journals: Pure and Applied Geophysics, Journal of Chemical and Engineering data, Exploration Geophysics, International Journal of Earth Sciences.**
- **Methods for determining thermal conductivity have been documented since the 1950's. This report will focus on more recent papers, fifteen of the nineteen papers examined in this report have been written since the 1990's.**

1.2 Thermal conductivity and its influences

The ease with which heat flows through a material can be measured and its quantity is called ‘thermal conductivity’ (Beardsmore & Cull 2001; Gunn et al. 2005). All results are consistently reported in W/mK which is ‘*the amount of heat in Watts flowing through a material per metre per Kelvin*’, the exception of a slight Middleton (1993) who has used W/m°C. W/mK is the current international standard for reporting the thermal conductivity of rocks. Other units that have been used are the British Thermal Unit per foot per degree Fahrenheit per hour (BTU ft⁻¹ °F⁻¹ hr⁻¹) and calories per centimetre per degree Celsius per second (cal cm⁻¹ C⁻¹ s⁻¹) (Beardsmore & Cull 2001). Thermal diffusivity, (in meters squared per second or m² s⁻¹), differs from thermal conductivity in that the diffusivity is the rate of change in temperature through a material or it is a measure of the speed of heat transfer (Beardsmore and Cull 2001). Thermal conductivity is a measure of how easily a quantity of heat will move through the same material.

Thermal conductivity is calculated by a combination of measurements and equations. Assuming that there is only a vertical component, heat flow models are created using Fourier’s Law of heat conduction (see Equation 1) combined with thermal conductivity and thermal gradient measurements (Clauser & Huenges 1995; Midtymme & Roaldset 1999).

$$Q = -\lambda \frac{dt}{dz}$$

Equation 1. Fourier’s Law of heat conduction. Q is the total amount of heat (Wm⁻²), λ is the thermal conductivity value (W/mK), dt is the change in temperature from initial to final and dz is the total distance of borehole/ thickness of sample (usually combined as the thermal gradient value, Km⁻¹) (Beardsmore and Cull 2001).

Thermal conductivity may be directly measured from rock samples or estimated from theoretical models using other data. For direct measurements of thermal conductivity the key parameters are: the rate of change in temperature over time, thickness and volume area of sample and any corrections for contact resistance (Beardsmore & Cull 2001). Estimates of thermal conductivity are based on assigned thermal conductivities of common lithologies combined with the property of the examined sample i.e. thermal diffusivity, porosity and mineral composition. A parameter that has not been well documented or taken into consideration in

calculation is the fluid content or degree of saturation of the sample. In one study there is a noticeable difference between a dry granite, 1.88 W/mK, and a wet granite, 2.52W/mK (Popov et al. 2003). Hydrological data, such as the salinity or water movement through formations, may need to be included in further geothermal studies.

Steady state methods may only give direct measurements of thermal conductivity whereas transient methods may directly measure thermal conductivity or measure other parameters to calculate it (Beck 1988).

1.2.1 Factors that affect thermal conductivity

Thermal conductivity is known to be influenced by three main factors: porosity, density and rock composition (Abdulagatov et al. 2006; Beardsmore & Cull 2001; Correia & Jones 1996; Midttymme & Roaldset 1999). Temperature and pressure are also important though their effects have not been well documented (Abdulagatov et al. 2006; Beardsmore & Cull 2001; Clauser & Huenges 1995). The lithologies of the samples may be tied in with the nature of the mineral content but as yet there is little definitive work on this (Clauser & Huenges 1995).

Anisotropy (which requires more study) is also an important key feature of sedimentary rocks but is less well researched (Midttymme & Roaldset 1999; Popov 2003; Vosteen & Schellschmidt 2003). If a rock is strongly anisotropic then heat may be directed sideways in the formation or at the formation boundary (Clauser & Huenges 1995). It is known that thermal conductivity parallel to bedding is twice that for thermal conductivity perpendicular to bedding due to the arrangement of crystals (Correia & Jones 1996; Midttymme & Roaldset 1999). Corrections may be applied to thermal conductivity measurements to take into account these factors.

1.2.2 Porosity

After rock composition, porosity is regarded as the most influential factor for sedimentary rocks (Clauser & Huenges 1995; Hartmann 2005; Matthews & Beardsmore 2007; Popov et al. 2003). A higher porosity allows greater fluid movement through a formation and hence greater transport of heat and thermal conductivities (Gunn et al. 2005). This is contradicted by Midttymme & Roaldset (1999) and Surma & Geraud (2003) who suggest decreasing porosity means a higher thermal conductivity. Either may be true as connectivity of pores and grain size will determine the permeability of a sample. Greater connectivity between pores will

allow fluid to move through a formation enabling heat to be transferred advectively and conductively much more quickly. Decreasing porosity due to greater compaction and hence closer contact of grains, allows greater conductive movement of heat across grains (Matthews & Beardmore 2007). It should also be noted that water content and porosity are two different parameters which should be analysed separately (Midttymme & Roaldset 1999).

1.2.3 Mineral content and lithology

Rock composition influences thermal conductivity more than anything else. Most sedimentary rocks are heterogeneous and therefore thermal conductivities will vary spatially over a formation (Matthews & Beardmore 2007; Popov et al. 2003). This results in a lot of uncertainty in measurements and for any average values calculated for a particular formation (Matthews & Beardmore 2007; Midttymme & Roaldset 1999).

Coarser sediments (sandstones) have higher thermal conductivities, possibly due to diminished grain-to-grain contacts and a smaller resistance to conduction, and *vice versa* for fine sediments (Midttymme & Roaldset 1999). It has been stated that lower thermal conductivities occur with lower porosities and increasing amounts of clay (Beardmore & Cull 2001; Popov et al. 2003). This seems to contradict the conclusions from other studies (Matthews & Beardmore 2007; Midttymme & Roaldset 1999; Surma & Geraud 2003) that greater compaction and lower porosities equal greater thermal conductivity. This disparity may be due to the clay platelets undergoing compaction causing them to orientate themselves in one direction and create a barrier to heat flow (Beardmore & Cull 2001). Hence leading to differences in thermal conductivities between fine grained lithologies.

Surma & Geraud (2003) also noted that samples with high thermal conductivities and porosities correlate with the presence of quartz in the cement and fractures. Recent studies noted that key minerals such as quartz or sulphides may induce a higher thermal conductivity between samples of the same lithology (Abdulagatov et al. 2006; Hartmann et al. 2005; Gunn et al. 2005; Midttymme & Roaldset 1999). Areas of concentrated quantities of sulphides and radiogenic elements, such as uranium ore bodies, may cause anomalies in heat flow models and need to be taken into account (Matthews & Beardmore 2007).

1.2.4 Temperature and pressure

As samples are brought to the surface, the release of pressure releases the stress on the core. This stress may have held fractures closed and compressed pores. Therefore it is expected that the release will affect the porosity and permeability of the samples (Abdulagatov et al. 2006; Gunn et al. 2005). The change in pressure on the sample will change the contact resistances on fractures and pores (Clauser & Huenges 1995). It is possible that thermal conductivity will decrease as decreasing pressure will create poorer grain-to-grain contact (Midttymme & Roaldset 1999).

Thermal conductivities appear to decrease with increasing temperature (negligible after 700°C) and increase with increasing pressure, though Abdulagatov et al. (2006) is alone in stating the impacts are significant (Abdulagatov et al. 2006; Midttymme & Roaldset 1999). It should be noted from theoretical models thermal conductivity estimates start to diverge significantly from direct measurements at greater than 80°C (Vosteen & Schellschmidt 2003). (See Image 1)

Current studies conclude that there is little variation in thermal conductivities with changes in pressure and temperature between different rock types (Clauser & Huenges 1995; Vosteen & Schellschmidt 2003).

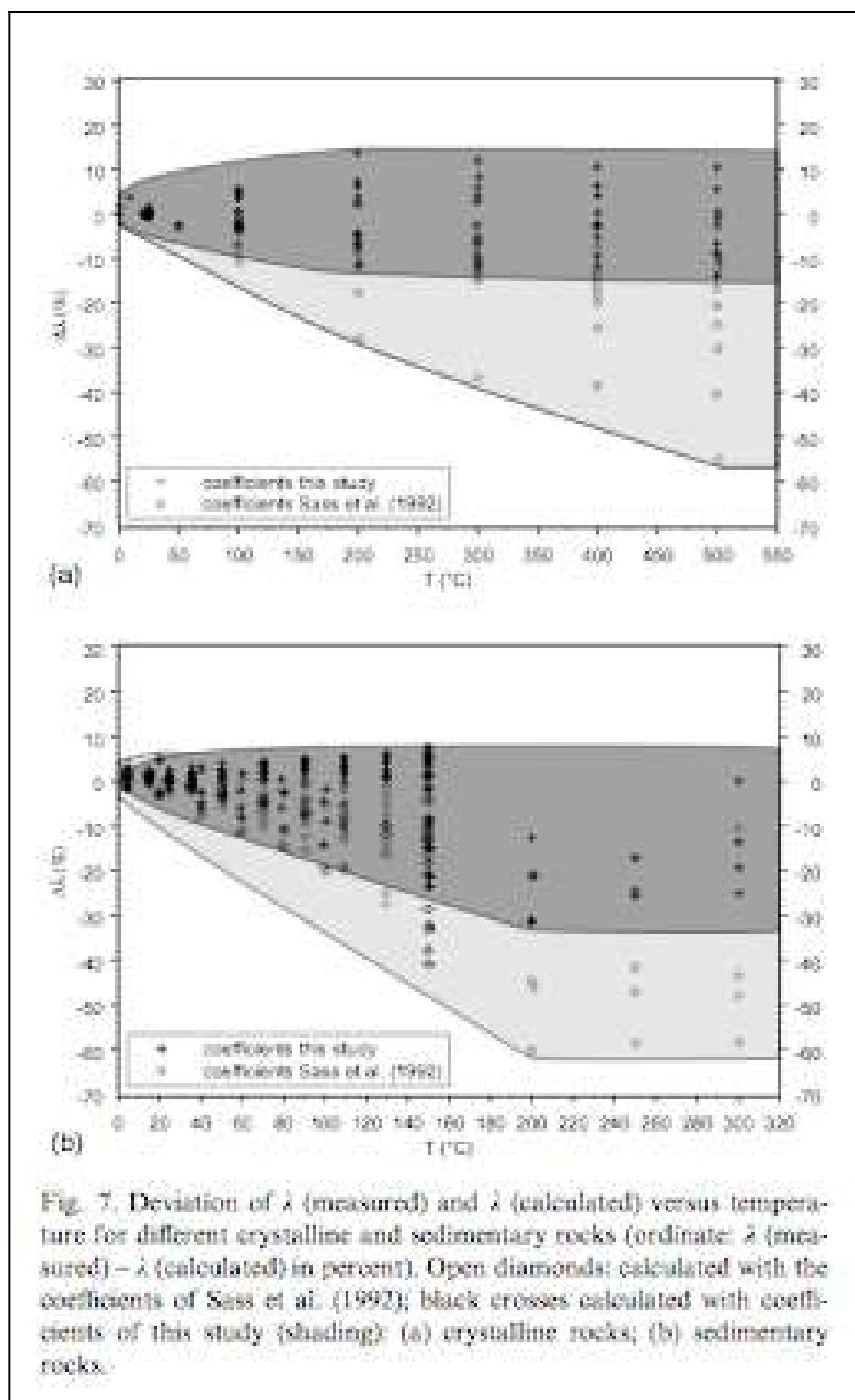


Fig. 7. Deviation of λ (measured) and λ (calculated) versus temperature for different crystalline and sedimentary rocks (ordinate: λ (measured) – λ (calculated) in percent). Open diamonds: calculated with the coefficients of Sasse et al. (1992); black crosses calculated with coefficients of this study (shading): (a) crystalline rocks; (b) sedimentary rocks.

Image 1.1. The dark grey area represents the deviation in direct thermal conductivity measurements with temperature and light grey area represents the deviation in calculated measurements (Vosteen & Schellschmidt 2003).

2. Methods for determining thermal conductivity

The type of sample available will determine what method is used. Samples may be consolidated or unconsolidated and either tested in a lab or *in situ*. Modifications may be made to geophysical devices to replicate *in situ* conditions such as high pressures and high temperatures i.e. placing samples in special chambers that can induce high pressures. However modifications to create high temperatures and pressure measurements are difficult to recreate in the lab. Instead corrections may be applied to any results (Gunn et al. 2005). Temperature corrections may be applied to a maximum depth of 6-10km (Beardmore & Cull 2001). Care must be taken not to damage samples. Samples placed under too much axial pressure develop artificial fractures and measurements at high temperatures may dry out saturated samples leading to erroneous thermal conductivities (Beck 1998; Midttymme & Roaldset 1999).

The two main empirical methods for determining thermal conductivity employ either steady state or transient methods, and each approach has its own advantages and disadvantages.

2.1 Transient methods

There are many variants of the transient method and these may be put into two classes: line source heat or point source heat. Either type may be used in the field or in the lab (Beardmore & Cull 2001; Beck 1988). Line source probes do require more power to heat the probe than point source probes and therefore may be unsuitable for long term field use (Beardmore & Cull 2001). The transient method refers to concentrating the heat input and the thermal conductivity measurement in small area rather than collecting a bulk rock thermal conductivity. Heat may be supplied in pulses over short times (~30 seconds) (Beardmore and Cull 2001).

2.1.1 Needle probe

The most commonly used transient device is the needle probe, containing either line or point source of heat (Beardmore & Cull 2001; Beck 1988; Vosteen & Schellschmidt 2003). Preferred samples are unconsolidated sediments though these types of devices work better on finer grained samples than coarser ones (Beck 1988).

2.1.1.1 Principles

In most cases the probe is inserted directly into a sample or plunged into the surrounding sediment (Beck 1988; Middleton 1993; Midttymme & Roaldset 1999). Laboratory probes are smaller, ~20cm in length, thinner and more fragile than those used in the field (see Image 2.1). Field probes are typically 10-30cm in length and when used in boreholes should ideally have the same diameter to as the hole (Beardsmore & Cull 2001).

Voltage is supplied at a constant rate to a heating coil or wire within the probe to produce heat. A thermal sensor, placed far enough from the heat source not to be affected by it, records the rate of temperature change from the surrounding sediment in response to the heat source (Beardsmore & Cull 2001; Middleton 1993)(see Image 2.2). The thermal conductivity may be measured directly, or more commonly as thermal diffusivity measurements that are then used to calculate thermal conductivity (Middleton 1993). (see Equation 2)

$$\lambda_s = (Q/4\pi) (\partial \ln(t) / \partial T)$$

Equation 2. To determine thermal conductivity solely from temperature readings. Q is the applied heat, λ_s determine once $\ln(t)$ versus T attains equilibrium (Beardsmore and Cull 2001).

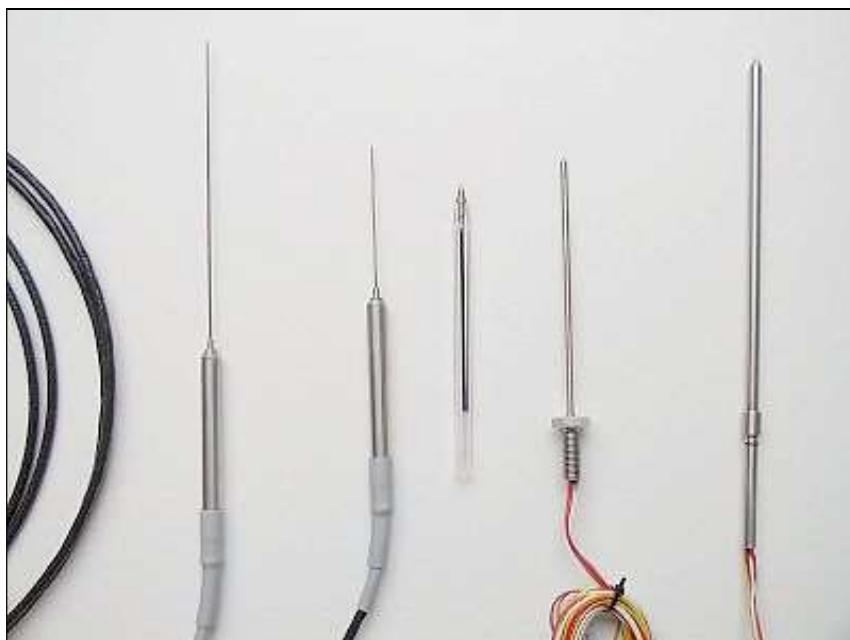


Image 2.1. These line-source needle probes are used in the lab. They are quite slim and small, a ball-point pen is used for scale (www.wikipedia.com)

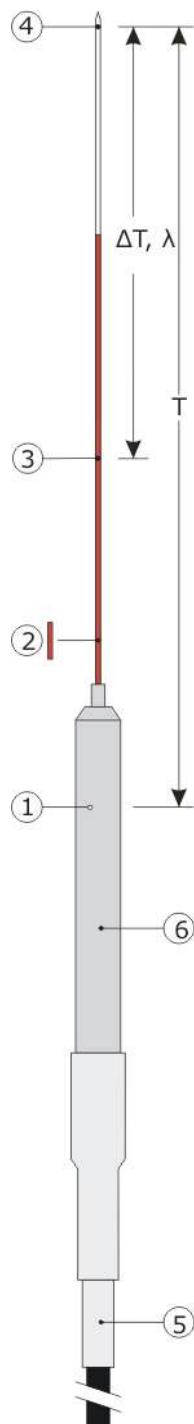


Image 2.2 'TP02 Non-Steady-State Probe consists of a needle with 2 thermocouple junctions (3), (4) (the tip acts as a reference) and a heating wire, (2). It is inserted into the medium that is investigated. In the base, (6), a temperature sensor, (1), is mounted. Advantages of this design: an optimal accuracy independent of the medium temperature, a minimal sensitivity to thermal gradients, a high sensor stability and the possibility to use normal cables and connectors. All dimensions are in mm' (www.hukseflux.com).

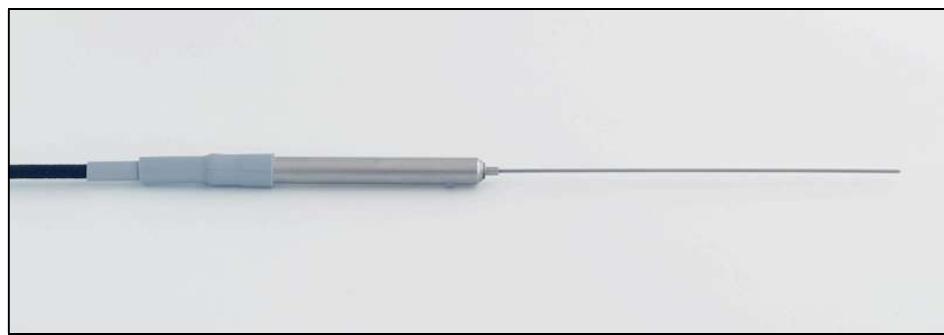


Image 2.3 Photograph of needle probe from diagram
(www.hukseflux.com).

2.2 Steady state methods

Steady state methods involve applying heat to the bulk of the sample until the heat is distributed evenly across the sample, unlike in transient methods where heat is concentrated in a particular area. The heat is applied at a constant and stable rate. The temperature is known on either side of the sample and measured in conjunction with a reference sample.

2.2.1 Divided bar

There is a general view that the Divided Bar is the most common steady state method used to measure thermal conductivity. It is recommended that this method be used for all consolidated samples only as unconsolidated samples require some difficult preparation (Beardsmore & Cull 2001; Beck 1988; Midtymme & Roaldset 1999). It is called a divided bar as the sample is placed in between two ends of a bar configuration (see Image 2.3).

2.2.1.1 Principles

This method has only been used in the lab; no true devices have been created for the field. Detailed descriptions of the divided bar can be found in a number of papers and books (Beardsmore & Cull 2001; Beck 1957; Beck 1988; Gunn et al. 2005; Vosteen & Schellschmidt 2003). The device is a bar, most commonly arranged vertically, with the hot plate at the top, the cold plate at the bottom and the rock sample sandwiched in between these two removable brass plates. (See image 2.3 and 2.4). The entire bar may be cylindrical or just the brass plates.

The unknown conductivity of the sample is measured against the known conductivity values of the brass plates. Thermocouples are inserted into the brass plates to record their precise temperature during testing. A thermal conductivity measurement is taken after the sample has attained equilibrium and the temperature drop across the sample is constant. The temperature range between the hot and cold plates may be controlled manually or by a thermostat. Heat is induced in the hot plate, which will flow downward through the sample and is kept at a constant rate (Gunn et al. 2005). This is to ensure heat flow through the sample is not a result of convection (Beardsmore & Cull 2001). The temperature drop across the sample is compared to

that across the brass plates and from this a thermal conductivity can be calculated. Insulation or a liquid coating on the sample may be used to stop heat loss from the sides of the sample to improve results (Beck 1988).

4.3. Measurements of Rock Conductivity

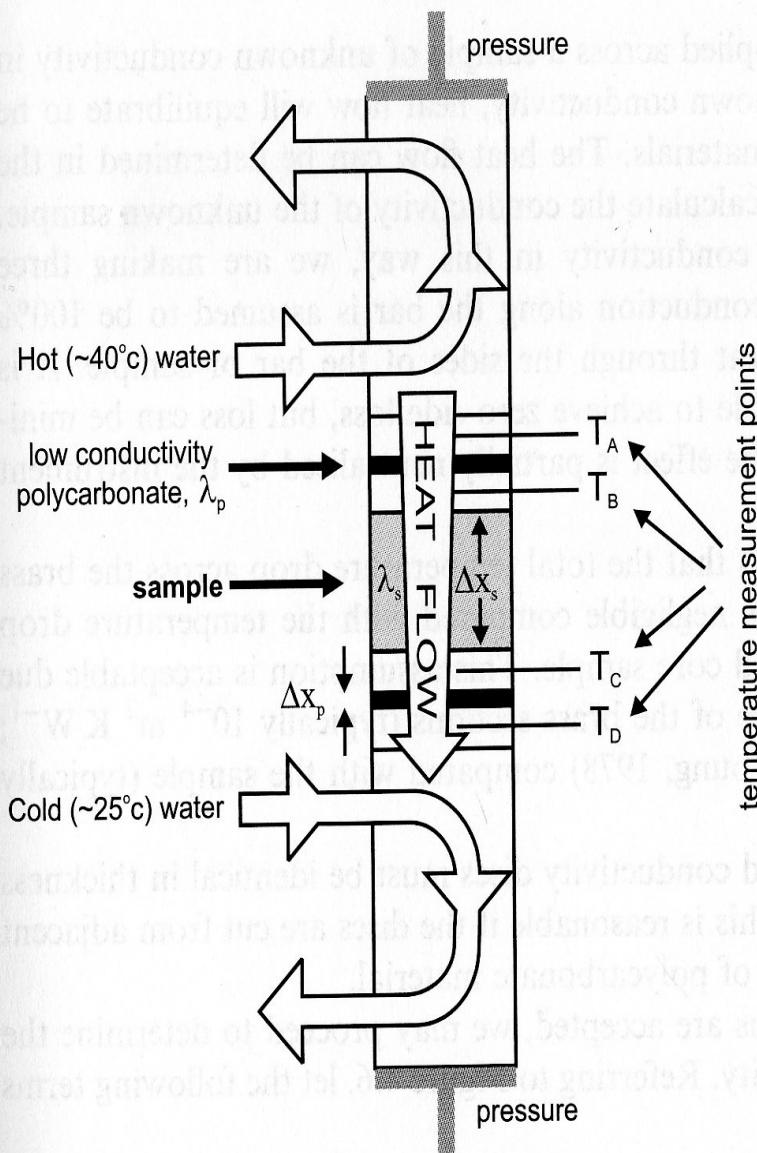


Figure 4.6. A typical divided-bar apparatus.

Image 2.3. The sample is the grey area in the middle of the bar. Fluid is pumped through the hot plate (top white area) and cold plate (bottom white area). Between the sample and the hot and cold plates are the brass plates containing the thermocouples (Beardsmore & Cull 2001).

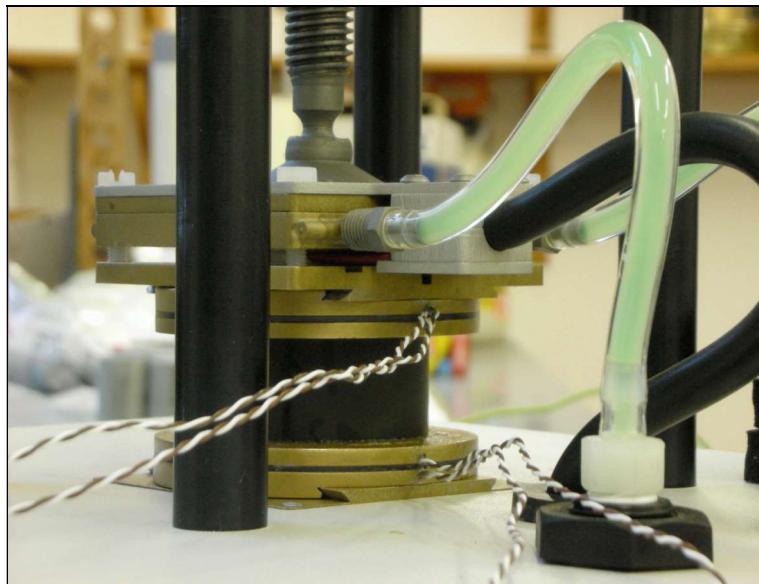


Image 2.4. In this image fluid enters one pipe (green) and exits from the other green pipe. The hot plate is square whereas the brass plate is circular. The hot plate is screwed down onto the sample. Only the top of the cold plate can be seen and it doesn't move at all. Brown and white stripe wires are the thermocouples.

The thickness and the nature of the sample will determine the time it takes for the sample to equilibrate i.e. in general the thicker the sample the longer it takes to reach equilibrium. The size of the samples are also limited by the power input and length of the device. A granite sample ~20mm thick may equilibrate after 10 minutes whereas siltstone of similar thickness will take ~30 minutes. To achieve more accurate results samples are heated until they reach equilibrium and this may take up to 20 minutes per sample compared to 10's of seconds for the needle probe (Beck 1957; Middleton 1993). Measurements at higher temperatures may take longer. Generally lower thermally conductive materials take longer to reach equilibrium.

Sample preparation is important and ideally the sample should have the same diameter and shape as the apparatus i.e. cylindrical samples for cylindrical disks (Beardsmore & Cull 2001; Beck 1988; Jaeger & Beck 1955; Midttymme & Roaldset 1999). It is possible that if the diameter of the sample is larger than the device then thermal conductivity will be higher and *vice versa* (Jaeger & Beck 1955). But this difference may be minimal and of not much concern. Samples may be prepared dehydrated or saturated (Gunn et al. 2005).

2.3 Advantages and disadvantages

One main advantage of the needle probe over the divided bar is the ease and speed with which measurements can be taken. *In situ* and lab measurements require little preparation, allowing large numbers of samples to be measured quickly (Beck 1988; Middleton 1993; Midttymme & Roaldset 1999). It is also possible to log the thermal conductivities over the entire borehole and different formations as well as in individual samples (Beardsmore & Cull 2001; Beck 1988; Popov et al. 2003). *In situ* temperature and pressure gradients may be taken into account when logging the complete hole (Beck 1988). Samples may be measured at high temperatures, to mimic *in situ* conditions, in the lab by increasing the voltage to the probe (Abdulagatov et al. 2006). It is also possible to measure the anisotropy of samples because the probe may be inserted into any part of the sample (Vosteen & Schellschmidt 2003).

The main disadvantages of the needle probe are the poor consistencies of results (Beck 1988), and the fact that any errors in measurement are harder to correct compared to steady state devices (Beck 1988). There is a consensus that errors are more likely to occur due to the nature of the contact resistances as the probe is inserted into the sediment (Beardsmore & Cull 2001; Beck 1988; Christoffel & Calhaem 1969; Gunn et al. 2005; Middleton 1993). For saturated samples with small volumes, heating of the sample may be too quick resulting in the sample drying out (Middleton 1993; Beck 1988). For *in situ* measurements, such as marine sampling, probes need to be plunged into the sediment making them vulnerable to damage (Beardsmore & Cull 2001; Beck 1988). In some instances the probe must be retrieved to collect each measurement and any damage won't register until it is brought back to the surface (Christoffel & Calhaem 1969).

The divided bar has more consistent and precise results than the needle probe (Gunn et al. 2005; Vosteen & Schellschmidt 2003). As for transient methods, contact resistance can lead to errors in measurement (Midttymme & Roaldset 1999). Contact resistance is much easier to correct by using gels, empirical and theoretical corrections (Beck 1957; Beck 1988; Correia & Jones 1996; Midttymme & Roaldset 1999; Vosteen & Schellschmidt 2003). Loss of heat from the sides of the sample may also be a problem but insulation around the sample can take care of this (Abdulagatov et al. 2006; Beardsmore & Cull 2001; Beck 1988; Vosteen & Schellschmidt 2003).

The divided bar may also be modified to measure stacked samples to mimic layering within formations (Beck 1957; Beck 1988). Steady state methods can also more accurately measure the variation with temperature on rocks than transient devices (Vosteen & Schellschmidt 2003).

Older devices with electric heaters take longer than the new and faster methods that employ water baths and fluids to maintain temperature gradient because electric heaters have to heat the material directly (Beck 1957; Beck 1988).

As steady state methods require competent rock samples, there may be bias in sampling towards particular units in a formation thus leading to different average thermal conductivities resulting from difference from *in situ* measurements (Gunn et al. 2005; Hartmann 2005). Hard rock samples may be damaged if too much axial pressure is applied by the divided bar thus leading to artificial fractures which create insulation within the sample (Beck 1988). Soft samples may be used but require very careful preparation and measurement, and the device has to be calibrated very accurately (Midttymme & Roaldset 1999).

The divided bar has lower uncertainties and errors than the needle probe. Inaccuracy is expected to be less than 5% and general errors to be less than 10% (Beck 1988; Middleton 1993). With improvements in technology divided bars may achieve smaller errors of about 5% (Beardsmore & Cull 2001; Correia & Jones 1996). Errors from contact resistance and heat loss are much easier to correct in steady state devices than in transient ones.

2.4 Summary

As yet there is no standard for sample preparation for each method. In each study samples were tested as only wet, only dry or both. A description how samples were saturated i.e fully saturated using vacuum pumps or left in a bucket for several days, is important as thermal conductivity may differ with different degrees of saturation.

The general consensus is that transient devices are not as accurate or reliable as steady state devices (Beck 1988). More corrections are needed to take into account errors and greater uncertainties in measurements due to variable contact resistances than for the divided bar approach. These transient methods which measure thermal diffusivity to calculate thermal conductivity may contain errors related to the formulae and calculations (Middleton 1993). In addition, errors from contact

resistance and heat loss are much easier to correct in steady state devices than in transient ones.

The error of needle probes is believed to be between 5-10%, a 5% error would make it comparable to the divided bar (Middleton 1993; Surma & Geraud 2003). Although measurements in the lab may be more consistent some papers recommend that the thermal gradient and thermal conductivity should be measured together *in situ* because they take into account hole conditions (Christoffell & Calhaem 1969). In some studies needle probes and divided bars are used together to compare thermal conductivity measurements from *in situ* and from drill core. Some results from a divided bar and *in situ* needle probe measurements correlate well. However the needle probe measurements in the lab, from the same study using the divided bar, were inconsistent and did not correlate well with *in situ* results. The drawback to *in situ* measurements is that they take longer than lab measurements due to the amount of energy required to heat the borehole (Beck 1988; Beardsmore & Cull 2001).

The divided methods are recommended to be used solely on consolidated material whereas the needle probe method should be used for soft sediments. Both steady state and transient methods may suffer from errors in long measurement times i.e. sedimentary rocks are sensitive to drying out (Beck 1957; Beck 1988; Midttymme & Roaldset 1999).

3. Other methods for determining thermal conductivity

3.1 High Resolution Optical Scanning

More recent papers (Förster et al. 2007; Hartmann et al. 2005; Hartmann et al. 2007; Popov et al. 2003) have opted to use a new transient method of Optical Scanning to measure thermal diffusivity, porosity, density and sonic velocity.

Optical Scanning directs a laser onto the surface of a core sample heating the point of measurement. A thermal sensor trails behind the laser as it scans over the core (Förster et al. 2007; Popov et al. 2003) (see Image 3.1). Thermal conductivity may be calculated for the entire core from the hole as well as on individual samples (Hartmann et al. 2005). The device does not directly measure thermal conductivity; instead it measures the thermal diffusivity of the sample, from which thermal conductivity is calculated. Other geophysical parameters such as sonic velocity and density can also be used to calculate thermal conductivity (Hartmann et al. 2005).

Another advantage is that the thermal conductivity may be measured at any angle to the core axis (Popov et al. 2003; Vosteen & Schellschmidt 2003). Thus allowing the structure and anisotropic nature to be considered.

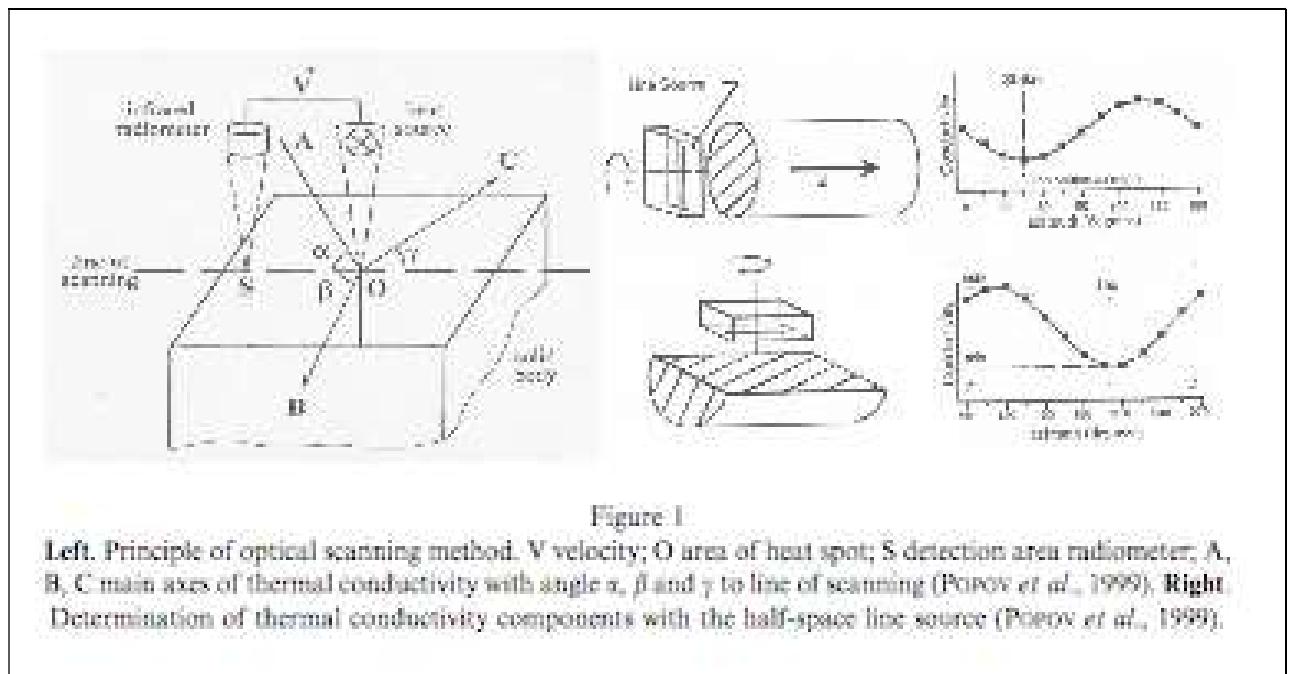


Figure 1

Left. Principle of optical scanning method. V velocity; O area of heat spot; S detection area radiometer; A, B, C main axes of thermal conductivity with angle α , β and γ to line of scanning (POPOV et al., 1999). **Right** Determination of thermal conductivity components with the half-space line source (POPOV et al., 1999).

Image 3.1 The grey image on the left depicts the position of the laser (left cone) and the thermal sensor (right cone) (Surma & Geraud 2003).

This may become the preferred method for measuring conductivity, as it is as quick as other transient methods, is non-destructive, very accurate and values are similar to or more precise than those from the divided bar (Popov et al. 2003). The measurement error of this device is believed to be about <2% (Surma & Geraud 2003). The method has been available since 1988 (Beck 1988) but is still only rarely due to being too complex to run and calibrate the lasers used in this device. It is not known what it currently costs to build and maintain such a device. It is possible that with further advancements in technology that the device has become more efficient, cheaper and easier to use. Recent devices, post 2005, may have multiple sensors allowing several measurements to be taken at the same time (Hartmann et al. 2005).

This type of device does not seem to be commercially available at this point in time.

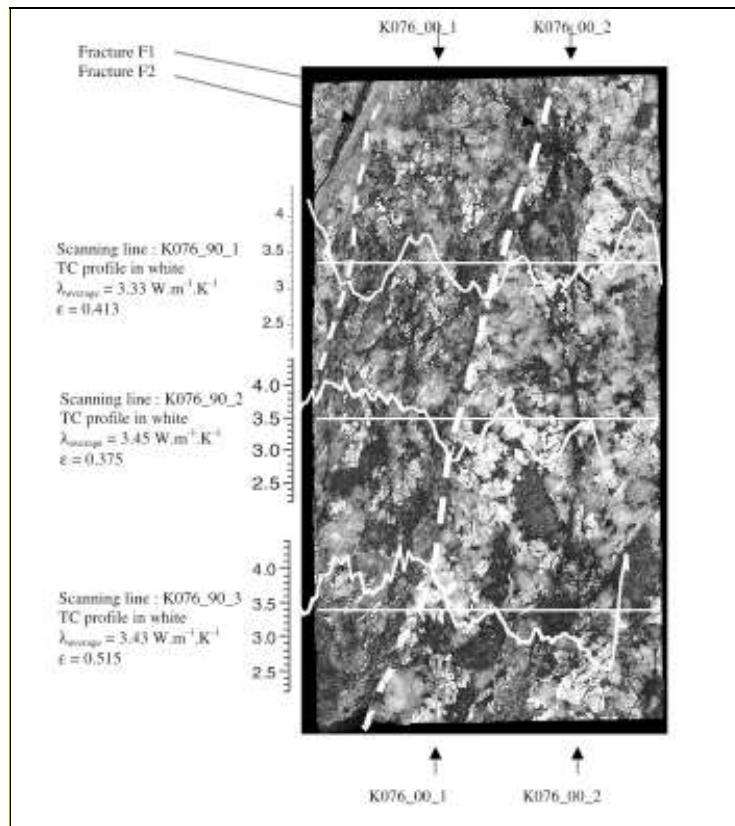


Image 3.2. The white squiggly lines depict the path of the laser and the area where thermal diffusivity has been recorded (Surma & Geraud 2003).

3.2 Well logs and theoretical models

Thermal conductivity may be determined using other empirical data, theoretical data or a mix of both (Hartmann et al. 2007). Wireline logs are an example of empirical data whereas theoretical thermal conductivities may be assumed values taken from other papers (Midttymme & Roaldset 1999). The most common logs are electrical/resistivity, density, neutron, self potential and gamma ray logs.

Wireline logs are used mainly in the petroleum industry to log petrophysical and thermal properties such as thermal diffusivity, porosity, permeability, density, sonic velocity and water volume (Beardsmore & Cull 2001; Hartmann et al. 2005; Hartmann et al. 2007). This data may be published and therefore acquired from reports, or the holes may still remain open, and hence be subjected to logging once exploration has ceased. As yet there seemed to be little correlation between resistivity profiles and thermal conductivities (Popov et al. 2003) and more study on the relationship between geophysical and thermal properties are required.

Generally well log data is used when there are no core samples available for testing (Correia & Jones 1996; Hartmann et al. 2005), a typical result in oil exploration in such cases thermal conductivity values are calculated using theoretical models combined with petrophysical data (Beardsmore & Cull 2001; Beck 1988). Theoretical models may also use mineral contents from the borehole or published values to estimate thermal conductivities (Beardsmore & Cull 2001; Beck 1988; Correia & Jones 1996).

Theoretical models, which use assigned thermal conductivity values, have difficulty in dealing with the individual texture and structure of units and are therefore prone to errors (Hartmann et al. 2007; Midttymme & Roaldset 1999). In addition there does not appear to be a standard model to use in modelling heat flow in sedimentary rocks (Midttymme & Roaldset 1999). The uncertainty for such models may be as great as 22%, far higher than for models based on transient or steady state models (Abdulagatov et al. 2006). (see Image 3.3).

It is very important to understand and document the limitations of models used in each study. The most effective and accurate models are those that take into account direct measurements of thermal conductivity, porosity, mineralogy and texture from the study area (Midttymme & Roaldset 1999).

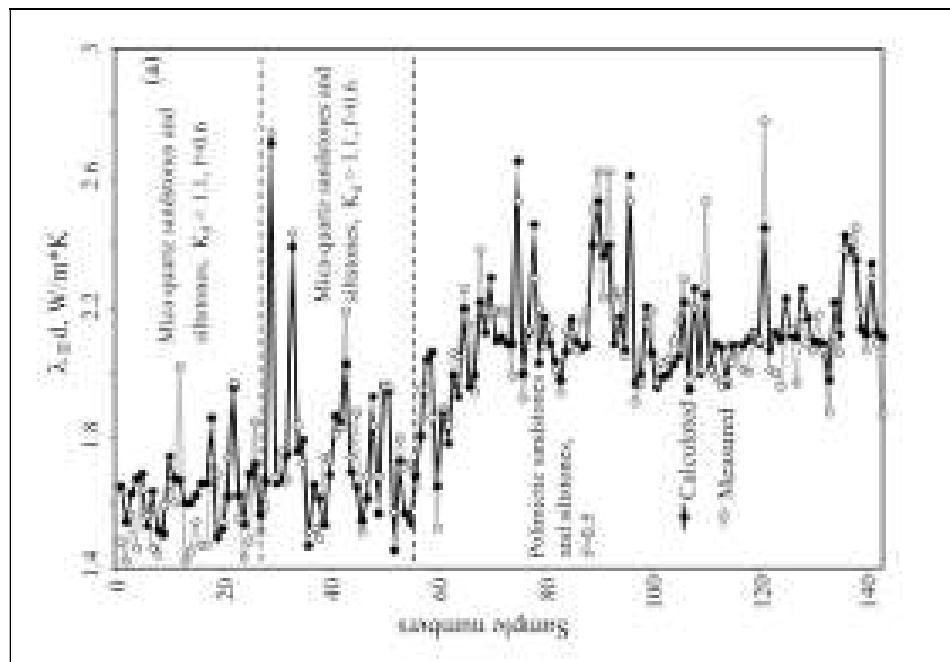


Image 3.3 Darker line depict calculated thermal conductivities, lighter grey lines depict thermal conductivities from direct measurements (Popov et al. 2003).

3.3 Rock crushing

In rare cases a method of crushing samples to a powder, turning them into a pressed pellet or solution, and then making thermal conductivity measurements on them (Midttymme & Roaldset 1999). The advantage of this is that (1) samples may be used with any device; (2) measurements can be quick; (3) and thermal conductivities may be measured from rock fragments. The disadvantages are (1) the large amount of preparation required; and (2) any measurements will not take into account the texture or structure of the rock unit. The accuracy of this kind of preparation is not known (Midttymme & Roaldset 1999)

4. Thermal conductivity values of common lithologies.

Values for sedimentary rocks vary across all papers and methods examined in this report (Abdulagatov et al. 2006; Beardsmore & Cull 2001; Middleton 1993; Midttymme & Roaldset 1999). Results for siltstones (1.78 up to 3.2 W/mK), shales (1.36 up to 2.9 W/mK) and granites (1.88 up to 3.5 W/mK) appear to have a smaller range than sandstones (1.66-7.1 W/mK) and a more consistent result (See Table 4.1 and Figure 4.1). Quartz values are very high compared to all other samples at 6.5 to 7.69 W/mK. It is suggested that needle probe measurements sometimes give higher results than the divided bar and the biggest difference between the two methods can be seen with unconsolidated sediments (Midttymme & Roaldset 1999).

4.1 Unconsolidated sediments

There is a general consensus that clays have a high variability (Beardsmore & Cull 2001; Hartmann et al. 2007; Midttymme & Roaldset 1999), but from the review of these papers the results for clay 1.08-2.39 W/mK have a range comparable to mudstones and limestones. A precise result from the Optical scanning method could not be attained (Hartmann et al. 2007). It is possible that the method is too precise and it is recording results from small numbers of individual grain characteristics rather than a representative conductivity of the sample. The only other result for clay (Matthews & Beardsmore 2007) was measured on a divided bar but there is no explanation how the soft samples were prepared for this device.

4.2 Consolidated sediments

Thermal conductivities for conglomerates were not mentioned in any papers. This could be due to the difficulty in sampling a representative section of a conglomerate layer as there will be differences in clast size from sorting and composition. Very thinly bedded units such as shales, mudstones and siltstones are usually contained as one sample.

4.2.1 Sandstones

The results for sandstone vary greatly from 1.66 up to 7.1 W/mK (see Figure 4.1). This variation in sandstone values may be due to differing quartz and feldspar contents between each sample and localities. Quartz-rich sandstones seem to have a thermal conductivity greater than 2.5W/mK. One value (Hartmann et al. 2005) using the Optical Scanner is very high, 5.14W/mK and another, using the same method, from a wet sandstone 6.21W/mK (Popov et al. 2003). One reported measurement for the needle probe is also relatively high, 4.69W/mK (Middleton 1993). Divided Bar measurements appear more consistent which range from 1.8-3.14W/mK.

4.2.2 Siltstones, Mudstones, Shales

Results for siltstones, mudstones and shales overlap with similar ranges, 1.2-4.77W/mK. Finer grain sizes and higher clay contents in the shales and mudstones do not seem to create smaller thermal conductivities than siltstones. Results from four divided bar studies for siltstones, mudstones and shales are consistent around 2-3W/mK. One needle probe measurement for shales/claystone is much lower at 1.34-1.88W/mK. The transient method may be much more sensitive to finer sediments than the divided bar method.

4.3 Carbonaceous sediments

Three divided bar and one needle probe measurements give a consistent range of 1.15-2.41W/mK (former) and 2.59W/mK (latter). The needle probe is higher than all the divided bar measurements. These results are slightly lower than for pure calcite, 3.6W/mK, and are most likely due to impurities in the limestone as it has formed and weathered.

4.5 Metamorphic rocks

Metamorphism of rocks will have a significant impact on thermal conductivity (Clauser & Huenges 1995). Quartzite has a thermal conductivity of 5.25-6.99 W/mK, which is very high relative to all other metamorphic, sedimentary and igneous rocks (Jones 2003). Quartz granulite has the lowest thermal conductivity, 1.77-2.37, despite being called a quartz granulite the proportion of plagioclase (see section 4.6) may be the determining factor of its' conductivity. The amphibolite and schist thermal conductivities are very similar, 2.35-3.99 for the former and 2.95-3.37 for the latter.

All results for metamorphic rocks in this review were measured on the divided bar. More results are needed to examine the effect of metamorphism and alteration on thermal properties (Clauser & Huenges 1995; Jones 2003).

4.4 Igneous rocks

More thermal conductivity data are gathered for granites than any other igneous rock type because these are the primary targets for heat generation in geothermal exploration. Granites have slightly higher thermal conductivities, 1.88-3.9W/mK, than unconsolidated or consolidated sediments. Discounting the dry measurement (1.88W/mK) from Popov's study (2003) granites have a range from 2.3-3.9W/mK. In the same study the wet results is 2.52W/mK indicating water content has a significant influence on the outcome of the measurement. More study is required to examine this relationship.

The single dolerite, 1.67W/mK, and lava, 1.5-1.66W/mK, values are very similar and are relatively lower with smaller ranges compared to other lithologies. The low result may be expected as they are comprised mainly of magnesium silicate which is used as an insulating material (Geller 2003). It is speculated that the SiO₂ content (quartz content) may determine the thermal conductivity of igneous rocks, i.e. felsic magmas (granites) have higher thermal conductivities than intermediate to basis magmas (basalts and dolerites).

4.6 Minerals

Quartz has the highest thermal conductivity of any rock or mineral examined so far, 6.5-8.3W/mK. As expected the quartzite and quartz rich values are higher than other lithologies. It is not known why quartz is such a good conductor of heat. Spaces between grains must be minimal to allow large quantities of heat to pass through the material. Plagioclase on the other hand has a typically low thermal conductivity, 2.15W/mK. Next are Muscovite (2.21W/mK), K-feldspar (2.32W/mK) and Calcite (3.6W/mK). A combination of sodium/aluminium or potassium/aluminium with silicates may dilute the thermal conducting capacities of minerals. Impurities within minerals may also result in different thermal conductivities.

These five minerals were tested in a steady state device and there appears to be no issue with the differences between quartz or the other minerals. A well logging and optical scanning result appear to correlate with the divided bar.

Table 4.1 Thermal conductivity results by lithology.

Lithology	Value W/mK	Method	Reference
Unconsolidated sediments			
Clay	1.08-2.39	Divided Bar	Matthew & Beardsmore 2007
	~2.0	Optical scanner	Hartmann et al. 2007
Consolidated sediments			
Sandstones	3.1-7.1	Review of other papers, unknown what methods were used	Beardsmore & Cull 2001
	1.97-2.83 and 1.66-2.47	Review of other papers, various methods	Midtymme & Roaldset 1999
	2.14-1.82 with increasing temperature	Divided Bar	Abdulagatov et al. 2006
	4.19	Divided Bar	Correia & Jones 1996
	2.24, corrected 6.47 at 30°C, (Q-rich) 2.52, corrected 2.92 at 30°C (Feldspar-rich)	Guarded Divided Bar	Gunn et al. 2005

Literature Review

	3.14	Divided Bar	Jones 2003
	5.14	Optical Scanner	Hartmann et al. 2005
	1.76-3.57 dry, 2.85-6.21 wet	Optical Scanner	Popov et al. 2003
	1.03-2.66 (fine grained) 2.33-3.89 (medium grained, Q-rich) 2.88 (coarse grained, Q-rich)	Optical Scanner	Förster et al. 2007
	4.69	Needle Probe	Middleton 1993
Siltstones	2.7-3.2	Review of other papers, unknown what methods were used	Beardsmore & Cull 2001
	2.68	Review of other papers, various methods	Midtymme & Roaldset 1999
	4.24	Divided Bar	Correia & Jones 1996
	3.31-4.41	Divided Bar	Jones 2003
	1.78-2.07, 2.54-2.82	Optical Scanner	Popov et al. 2003
Interbedded siltstone and shales	1.19-1.78, 2.20-3.10	Optical Scanner	Popov et al. 2003
Mudstones and shales	1.5-2.9	Review of other papers, unknown what methods were used	Beardsmore and Cull 2001
	1.36-2.46	Review of other papers, various methods	Midtymme & Roaldset 1999
	2.30-3.11	Divided Bar	Correia & Jones 1996
	1.88-4.77	Divided Bar	Jones 2003
	1.34-1.88	Needle Probe	Middleton 1993

Carbonaceous sediments			
Limestones	1.55-2.25	Divided Bar	Abdulagatov et al. 2006
	2.41	Divided Bar	Correia & Jones 1996
	1.15-2.39	Divided Bar	Matthews & Beardsmore 2001
	2.59	Needle Probe	Middleton 1993
Metamorphic rocks			
Amphibolite	2.35-3.99	Divided Bar	Abdulagatov et al. 2006
Quartz granulite	1.77-2.37	Divided Bar	Abdulagatov et al. 2006
Schist	2.95-3.37	Divided Bar	Matthews & Beardsmore 2001
Quartzite	5.25-6.99	Divided Bar	Jones 2003
Igneous rocks			
Granite	2.8-3.5	Review of other papers, unknown what methods were used	Beardsmore and Cull 2001
	2.79-2.95	Divided Bar	Matthews & Beardsmore 2001
	1.88 dry 2.52 wet	Optical Scanner	Popov et al. 2003
	2.3-3.9	Needle Probe and Optical Scanner	Surma & Geraud 2003
Dolerite	1.67	Needle Probe	Middleton 1993
Lava	1.5-1.66	Divided Bar	Matthews & Beardsmore 2001
Minerals			
Quartz	7.7-8.3	Guarded Divided Bar	Gunn et al. 2005
	6.5	Optical Scanner	Förster et al. 2007
	7.69	Well logging	Hartmann et al. 2005
K-feldspar	2.32	Guarded Divided Bar	Gunn et al. 2005
Calcite	3.6	Guarded Divided Bar	Gunn et al. 2005
Muscovite	2.21	Guarded Divided Bar	Gunn et al. 2005
Plagioclase	2.15	Guarded Divided Bar	Gunn et al. 2005

There appear to be no distinct differences between results and the type of method used. A table of values is not an appropriate way to display the results for each lithology (Clauser & Huenges 1995). The same data in Table 4.1 is also displayed in Figure 4.1 to better compare the results between lithologies.

A ternary diagram based on mineral content and thermal conductivity may be more accurate way to explain the relationship between grainsize, mineral composition and lithology (see Image 4.1). Separate ternary diagrams may be created for igneous and sedimentary rocks. Quartz content, clay content, porosities and grain size could be plotted along side thermal conductivity.

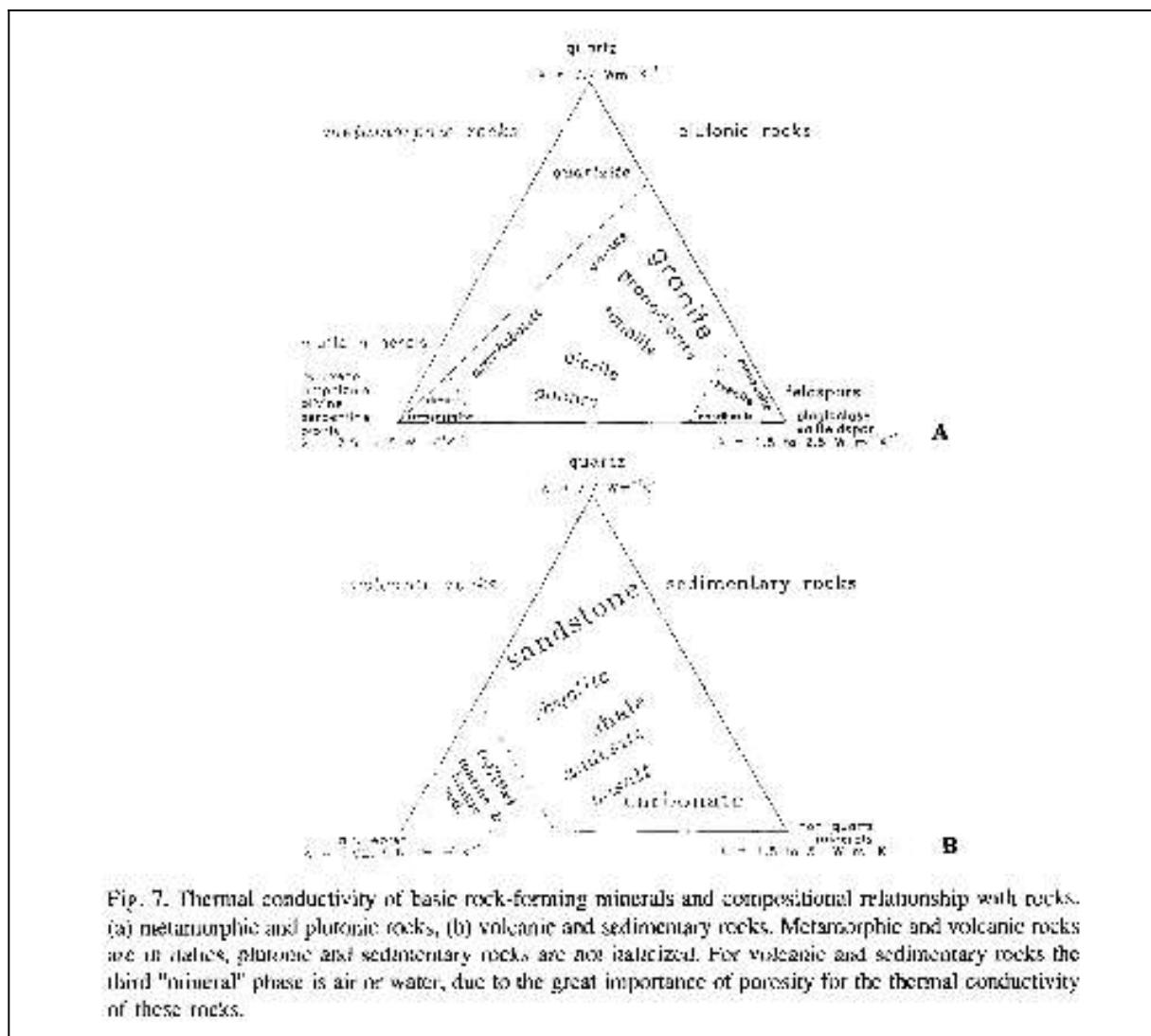


Fig. 7. Thermal conductivity of basic rock-forming minerals and compositional relationship with rocks. (a) metamorphic and plutonic rocks, (b) volcanic and sedimentary rocks. Metamorphic and volcanic rocks are in italics, plutonic and sedimentary rocks are not italicized. For volcanic and sedimentary rocks the third "mineral" phase is air or water, due to the great importance of porosity for the thermal conductivity of these rocks.

Image 4.1. Displaying separate ternary diagrams for igneous and sedimentary rocks based on mineral composition (Clauser & Huenges 1995).

Figure 4.1. Relative thermal conductivities of common rocks and minerals in W/mK.

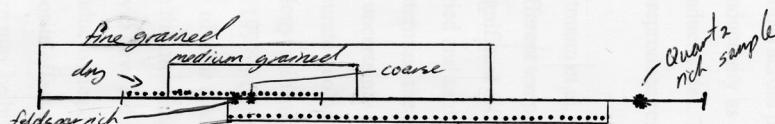
1. Unconsolidated sediments

Clay¹



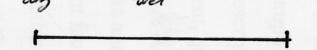
2. Consolidated sediments

Sandstone²



Siltstone³

dry wet

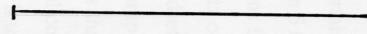


Mudstone⁴

Shale⁵

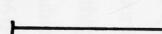
Interbedded siltstones
and shales⁶

dry wet



3. Carbonaceous sediments

Limestone⁷



4. Metamorphic rocks

Amphibolite⁸



Quartz granulite⁹



Schist¹⁰



Quartzite¹¹



4. Igneous rocks

Granite¹²



Dolerite¹³



Lava¹⁴



Figure 4.1 cont.

5. Minerals

Quartz¹⁵



K-feldspar¹⁶



Calcite¹⁶



Muscovite¹⁶



Plagioclase¹⁶



W/mK



¹ (Matthews & Beardmore 2007; Hartmann et al. 2007)

² (Abdulagatov et al. 2006; Beardmore & Cull 2001; Correia & Jones 1996; Förster et al. 2007; Gunn et al. 2005; Hartmann et al. 2005; Jones 2003; Middleton 1993; Midttymme & Roalset 1999)

³ (Beardmore & Cull 2001; Midttymme & Roalset 1999; Correia & Jones 1996; Jones 2003; Popov et al. 2003)

⁴ (Beardmore & Cull 2001; Midttymme & Roalset 1999; Correia & Jones 1996; Jones 2003; Middleton 1993)

⁵ (Beardmore & Cull 2001; Correia & Jones 1996; Jones 2003; Middleton 1993; Midttymme & Roalset 1999)

⁶ (Popov et al. 2003)

⁷ (Abdulagatov et al. 2006; Matthews & Beardmore 2001; Correia & Jones 1996; Middleton 1993)

⁸ (Abdulagatov et al. 2006)

⁹ (Abdulagatov et al. 2006)

¹⁰ (Matthews & Beardmore 2001)

¹¹ (Jones 2003)

¹² (Beardmore & Cull 2001; Matthews & Beardmore 2001; Popov et al. 2003; Surma & Geraud 2003)

¹³ (Middleton 1993)

¹⁴ (Mathews & Beardmore 2001)

¹⁵ (Gunn et al. 2005; Hartmann et al. 2005; Förster et al. 2007)

¹⁶ (Gunn et al. 2005)

5. Standards and procedures for measurement

5.1 Standards of measurement and reporting

Beck (1988) and Midtymme & Roaldset (1999) maintain that the variation in the way the thermal conductivities are reported makes it difficult to compare values across papers. Some papers (Gunn et al. 2005; Popov et al. 2003) list thermal conductivity as a single value whereas others list dry, saturated and corrected thermal conductivities. This lack of standardisation in procedures may make it difficult to reproduce results from other papers (Beck 1988; Midtymme & Roaldset 1999).

Hartmann et al. (2005) and Middleton (1993) have stated that samples may be tested at different temperatures and prepared in different ways. It should be noted that there are significant differences in the thermal conductivity of the same sample after it has been dried and saturated. It is important to know how samples were prepared and tested to determine the degree of uncertainty in measurements. Between dry and wet sample the uncertainty may jump from 5 to 10% (Middleton 1993).

Accurate geological descriptions for all samples should include contributions under lithology, mineral content, quartz content and preparation of sample for testing (Middleton 1993; Midtymme & Roaldset 1999). Some papers do adequately describe the geology of their study areas and samples, for instance quartz and clay content of samples are the most important factors that should be reported i.e. a quartz rich sandstone will have a different thermal conductivity to lithic rich sandstone. Recent thermal conductivities of quartz show it to be a good conductor of heat whereas clay has the opposite effect (Jones 2003; Correia & Jones 1996).

There may be big differences between predicted and direct measurements because all study areas will vary from one another (Midtymme & Roaldset 1999). An example reports a measured value of 2.6W/mK for a limestone whereas the estimate, based on a theoretical model, was 3.6W/mK (Hartmann et al 2007). Variations in published results may be due to poor quality measurements and sample preparation (Midtymme & Roaldset 1999).

5.2 Errors and uncertainty

All measurements collected in the lab need to be corrected for *in situ* temperature and pressure conditions (Beardsmore & Cull 2001). Samples are subjected to errors from loss of heat from the sides, contact resistances and degree of saturation during measurement. The heterogeneous nature of sedimentary rocks will also lead to variability in measurements and higher uncertainties in results (Matthews & Beardsmore 2007).

Transient devices are more likely to produce errors in measurement and therefore have a higher uncertainty than steady state devices. This may be due to drying out of the sample from too much heat from the probe and contact errors as it is inserted into the sample (Becks 1988). Errors in steady state devices can be corrected more easily than transient ones. It is recommended each device should have an imprecision of 2% and an inaccuracy of 5%. Technical errors such as loose thermocouples and insufficient amounts of gel on surface contacts may also give errors in measurement (Beck 1988).

5.3 Calibration of devices

Calibration of all devices are recommended to take place before any measurements (Beardsmore & Cull 2001; Beck 1988; Abdulagatov et al. 2006). An international standard of either a fused quartz or crystalline quartz disk should be used to calibrate a device though most papers do not state if any calibration took place (Beck 1988). All papers should describe how their devices were calibrated and the confidence of sample measurements.

6. Recommendations for measuring and reporting thermal conductivity data

Although published in 1988, Becks paper on the methods for measuring thermal conductivity is still highly relevant and useful for present research. He has made every effort to describe all factors involved. He would like to see authors (such as Vosteen & Schellschmidt 2003) be more detailed and descriptive of their experiments and samples. It is recommended that there be more comparative studies on the methods and results for sedimentary rocks (Midttymme & Roaldset 1999). A

recent publication '*Crustal heat flow: a guide to measurement and modelling*' by Beardsmore & Cull (2001) thoroughly details current methods and procedures for collecting thermal data.

To create more accurate models, it is better to use measured values from the project area as there are lots of variations between measured and published values (Correia & Jones 1996; Hartmann et al. 2007). Therefore empirical models are recommended as they are more accurate than theoretical estimates (Abdulagatov et al. 2006; Popov et al. 2003). In one case the measured thermal conductivities were twice those from assumed values based on global averages (Correia & Jones 1996). It is important to take representative samples of geological formations due variations within the unit (Abdulagatov et al. 2006; Beardsmore & Cull 2001; Beck 1988; Correia & Jones 1996; Hartmann et al. 2005; Hartmann et al. 2007; Matthews & Beardsmore 2007; Midtymme & Roaldset 1999).

Accurate descriptions of the way samples are prepared and tested are important to determine the uncertainty surrounding measurements (Middleton 1993). It is also recommended that collecting density and porosity measurements for all samples become a standard procedure to enhance the database of rock properties (Beardsmore & Cull 2001; Middleton 1993; Vosteen & Schellschmidt 2003).

All papers acknowledge that rock composition, and then porosity, have a stronger affect on thermal conductivity than temperature and pressure (Beardsmore & Cull 2001; Clauser & Huenges 1995; Correia & Jones 1996; Hartmann et al. 2005; Jones 2003; Midtymme & Roaldset 1999; Popov et al. 2003). Quartz and clay contents play a key role in determining thermal conductivities.

Vosteen & Schellschmidt (2003) states sedimentary rocks have higher thermal conductivities than igneous or metamorphic rocks. Though from the previous section results for all three rock types overlap each other within the 0-5 W/mK band. The exceptions are sandstones with results reaching 7 W/mK, and quartzites, 5.25-6.99 W/mK. Their conclusion could be the result from their sedimentary samples being slightly metamorphosed.

Metamorphosis of sedimentary rocks needs to be taken into account when using temperature estimates in heat flow models. Metamorphosis and degree of alteration will change the structure and composition of sedimentary rocks around 300°C (Förster et al. 2007; Hartmann et al. 2005; Vosteen & Schellschmidt 2003). Results for quartzite indicate a very high thermal conductivity, 5.25-6.99 W/mK,

indicating that as sandstones are altered thermal conductivity increases (Jones 2003). Therefore models that estimate consolidated sediment rock thermal conductivities should be limited to 300°C because after this the rocks should be considered metamorphic.

Perhaps papers should also try to explain the relationship between lithology and thermal conductivity more closely (Beardmore & Cull 2001; Beck 1988; Hartmann et al. 2007). Exploring the relationship between thermal conductivity and rock properties is still a relatively new field of research requiring more collection and analysis of data. It is recommended that future studies explore the relationships between anisotropy in sedimentary rocks, intrusion composition, the effect of grainsize in igneous intrusions, fluid content and fluid conductivity with respect to thermal conductivity (Popov et al. 2003).

Advancement in this field has been the optical scanning device which has an accuracy comparable to the divided bar. It is able to log thermal conductivities of entire cores quickly and efficiently making it attractive for large studies.

7. Conclusion

The divided bar is more appropriate for consolidated samples, whereas the needle probe is most applicable for soft sediments. Although measurements may take longer, steady state methods are recommended for lab samples as they give more consistent and accurate results. Any errors may be corrected more easily than for transient measurements, and testing conditions are more easily controlled in the lab. Transient methods are predominantly better for *in situ* measurements which can take into account temperature and pressure conditions. Calibration of devices should also be undertaken before any measurements take place.

Steady state methods give more accurate and consistent results than transient methods with the exception of the optical scanning method. With time and further improvements optical scanning may become a more efficient and convenient method than the divided bar.

There appears to be some consensus for igneous rocks and finer grained sedimentary rocks. Determining a definitive value for sandstones will take further

research into the relationship between feldspar and quartz content and thermal conductivity.

Using empirical values are recommended rather than theoretical values for heat flow modelling. Models based on petrophysical characteristics alone run a risk of significant error because the effects of texture and structure have been shown to be substantial. Currently it appears that porosity and rock composition are the main factors controlling thermal conductivity. Most papers report their results without exploring the relationship between the different petrophysical and thermal properties.

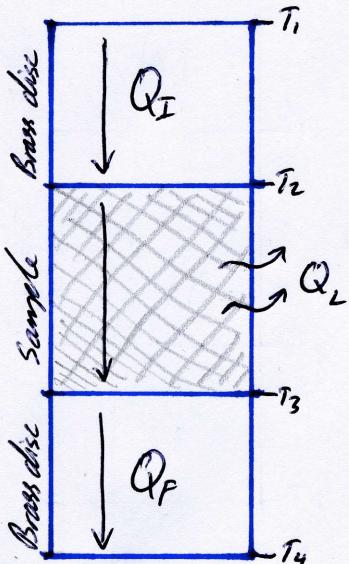
There still needs to be a standardised method of measuring and reporting thermal conductivity values.

(References can be found at the end of the thesis)

Appendix 2

FQ A.1 by M. Roach

Heat loss from the sides of the sample.



i) Assume no heat lost from the brass discs.

2) Q_L is the heat lost from the sample.

Case 1 $Q_L = \text{zero heat lost}$

The PEDB calculates the "average" heat flow (Q_A) from the heat flow through the top and bottom brass discs.

$$Q_A = Q_I = Q_F \therefore \frac{Q_I + Q_F}{2}$$

Case 2 $Q_L \neq 0$

The calculations then use the Q_A value to compute the thermal conductivity of the sample by equations the average heat flow to the heat flow implied by the thermal conductivity of the sample plus the measured temperature difference.

$$Q_I = Q_L + Q_F$$

$$Q_A = \frac{Q_I + Q_F}{2} = \frac{Q_L + Q_F + Q_F}{2} = \frac{2Q_F + Q_L}{2}$$

$$Q_A = \frac{2Q_F + Q_L}{2} = \lambda_s \frac{\Delta T_s}{\Delta x_s}$$

$$\Rightarrow \lambda_s = \frac{(2Q_F + Q_L) * \Delta x_s}{\Delta T_s} \therefore Q_L \uparrow \text{then } \lambda_s \uparrow$$

as heat loss increases the thermal conductivity increases.

Appendix 3. Error propagation

Errors are propagated through all measurements and calculations using the precision of measurement.
One example is given below.

Heat capacity equation.

$$HC_r = \frac{M_w * HC_w(T_2 - T_1)}{M_s(T_d - T_2)}$$

Sample No.		Precision	
mass of sample g	M_s	Temp oven	1 C
mass of water g	M_w	Temp TC	0.5 C
Initial water temp C	T_1	Mass	0.1 g
Final water tempC	T_2	HC water	0.01
Initial sample temp C	T_d		
Heat capacity of water J/gK	HC_w		
HC of sample J/gK	HC_r		

Error propagation for the numerator

$$[(0.1/M_w)*100] + [(0.01/HC_w)*100] + [0.5+0.5/(T_2-T_1)*100]$$

Error propagation for the denominator

$$[(0.1/M_s)*100] + [0.5+0.5/(T_d-T_2)*100]$$

Add the results from the numerator and denominator together to get the total percentage error.

Appendix 4. Rock catalogue
More information can be found in the digital appendices.

Utas#	Field Number	Rock Name	Meta-morphism	State	Map grid Northing	Map grid Easting	Period/System	Hand specimen	Thin Section	Polished block
161051	HG01	Sandstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161052	HG02	Sandstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161053	HG03	Sandstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161054	HG04	Sandstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161055	HG05	Sandstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161056	HG06	Sandstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R	1TS	PB
161057	HG07	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R	1TS	
161058	HG08	Siltstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161059	HG09	Siltstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161060	HG10	Siltstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R	1TS	PB
161061	HG11	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161062	HG12	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161063	HG13	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161064	HG14	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161065	HG15	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161066	HG16	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		PB
161067	HG17	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161068	HG18	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161069	HG19	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161070	HG20	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161071	HG21	Mudstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		PB
161072	HG22	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161073	HG23	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161074	HG24	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161075	HG25	Sandstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161076	HG27	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161077	HG28	Sandstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161078	HG29	Shale	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161079	HG30	Mudstone	low grade	Tasmania	5413068mN	572602mE	Silurian	R		
161080	HG42	Shale	low grade	Tasmania	5414380mN	583650mE	Silurian	R	1TS	
161081	HG43	Siltstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161082	HG44	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161083	HG45	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R	1TS	
161084	HG46	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161085	HG47	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R	1TS	PB
161086	HG48	Siltstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R	1TS	PB
161087	HG49	Siltstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R	1TS	
161088	HG50	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161089	HG51	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161090	HG52	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161091	HG53	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161092	HG54	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R	1TS	PB
161093	HG55	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161094	HG56	Siltstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161095	HG57	Sandstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R	1TS	
161096	HG58	Siltstone	low grade	Tasmania	5414380mN	583650mE	Silurian	R		
161097	HG59	Sandstone	low grade	Tasmania	5417571mN	569614mE	Silurian	R	1TS	PB
161098	HG60	Shale	low grade	Tasmania	5417571mN	569614mE	Silurian	R	1TS	
161099	HG61	Sandstone	low grade	Tasmania	5417571mN	569614mE	Silurian	R		
161100	HG62	Siltstone	low grade	Tasmania	5417571mN	569614mE	Silurian	R		
161101	HG63	Sandstone	low grade	Tasmania	5417571mN	569614mE	Silurian	R		
161102	HG64	Siltstone	low grade	Tasmania	5414880mN	601900mE	Silurian	R		
161103	HG65	Mudstone	low grade	Tasmania	5414880mN	601900mE	Silurian	R	1TS	PB
161104	HG66	Siltstone	low grade	Tasmania	5414880mN	601900mE	Silurian	R		

Utas#	Field Number	Rock Name	Meta-morphism	State	Map grid Northing	Map grid Easting	Period/ System	Hand specimen	Thin Section	Polished block
161105	HG67	Sandstone	low grade	Tasmania	5414880mN	601900mE	Silurian	R		
161106	HG68	Mudstone	low grade	Tasmania	5414880mN	601900mE	Silurian	R	1TS	PB
161107	HG69	Mudstone	low grade	Tasmania	5414880mN	601900mE	Silurian	R		
161108	HG70	Siltstone	low grade	Tasmania	5414880mN	601900mE	Silurian	R		
161109	HG71	Sandstone	low grade	Tasmania	5414880mN	601900mE	Silurian	R		
161110	HG72	Granite		Tasmania	543561.64mN585189.61mE	Devonian		R		
161111	HG73	Granite		Tasmania	543561.64mN585189.61mE	Devonian		R		PB
161112	HG74	Granite		Tasmania	543561.64mN585189.61mE	Devonian		R		
161113	HG75	Granite		Tasmania	543561.64mN585189.61mE	Devonian		R		
161114	HG76	Granite		Tasmania	543561.64mN585189.61mE	Devonian		R		
161115	HG77	Granite		Tasmania	543561.64mN585189.61mE	Devonian		R		PB
161116	HG78	Granite		Tasmania	5384050mN	560250mE	Devonian	R		
161117	HG79	Granite		Tasmania	5384050mN	560250mE	Devonian	R		
161118	HG80	Granite		Tasmania	5384050mN	560250mE	Devonian	R		
161119	HG81	Granite		Tasmania	5384050mN	560250mE	Devonian	R		PB
161120	HG82	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161121	HG83	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161122	HG84	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161123	HG85	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161124	HG86	Granite		Tasmania	5336600mN	606200mE	Devonian	R		PB
161125	HG87	Granite		Tasmania	5336600mN	606200mE	Devonian	R	1TS	PB
161126	HG88	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161127	HG89	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161128	HG90	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161129	HG91	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161130	HG92	Granite		Tasmania	5336600mN	606200mE	Devonian	R	1TS	PB
161131	HG93	Granite		Tasmania	5336600mN	606200mE	Devonian	R	1TS	PB
161132	HG94	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161133	HG95	Granite		Tasmania	5336600mN	606200mE	Devonian	R		
161134	HG96	Granite		Tasmania	5368276.5mN	573358mE	Devonian	R		
161135	HG97	Granite		Tasmania	5368276.5mN	573358mE	Devonian	R	1TS	PB
161136	HG98	Granite		Tasmania	5368276.5mN	573358mE	Devonian	R		
161137	HG99	Granite		Tasmania	5368276.5mN	573358mE	Devonian	R		
161138	HG100	Granite		Tasmania	5368276.5mN	573358mE	Devonian	R		
161139	HG101	Granite		Tasmania	5368276.5mN	573358mE	Devonian	R		
161140	HG102	Granite		Tasmania	5368276.5mN	573358mE	Devonian	R		PB

Appendix 4 cont. Dimensions of samples

Sample No.	Diameter mm	Thickness mm	Volume mm³
HG No01	45.06	78.51	11113.89
HG No02	45.10	79.70	11286.64
HG No03	45.15	79.50	11270.79
HG No04	45.11	81.31	11517.19
HG No05	45.11	81.27	11511.52
HG No06	45.14	78.75	11161.99
HG No07	45.15	79.48	11267.96
HG No08	45.13	78.18	11078.75
HG No09	45.15	78.00	11058.14
HG No10	45.16	79.23	11235.00
HG No11	45.15	77.80	11029.78
HG No12	45.30	70.64	10047.97
HG No13	45.20	42.51	6033.36
HG No14	45.23	82.08	11657.18
HG No15	45.17	58.32	8271.75
HG No16	45.20	80.01	11355.66
HG No17	45.19	48.00	6811.04
HG No18	45.33	77.91	11089.41
HG No19	45.14	76.34	10820.40
HG No20	45.19	77.22	10957.26
HG No21	44.83	79.40	11176.84
HG No22	45.02	26.15	3696.64
HG No23	45.00	80.11	11319.54
HG No24	45.02	64.74	9151.83
HG No25	45.14	79.88	11322.16
HG No26	destroyed		
HG No27	44.50	78.72	10999.55
HG No28	44.69	65.77	9229.28
HG No29	47.71	76.66	11484.39
HG No30	45.02	68.17	9636.70
HG No41	test sample		
HG No42	47.23	82.65	12257.18
HG No43	test sample		
HG No44	47.22	80.05	11869.08
HG No45	47.26	80.15	11893.97
HG No46	47.32	81.19	12063.60
HG No47	47.16	80.82	11968.02
HG No48	47.46	78.97	11768.46
HG No49	47.48	76.55	11412.63
HG No50	47.49	78.85	11758.00
HG No51	47.50	80.75	12043.86
HG No52	47.61	78.19	11689.05
HG No53	47.28	80.40	11936.12
HG No54	47.44	79.33	11817.12
HG No55	47.31	80.71	11989.74
HG No56	46.97	80.82	11919.80
HG No57	47.30	81.26	12075.02

Appendix 4. cont.			
Sample No.	Diameter mm	Thickness mm	Volume mm ³
HG No58	47.28	78.73	11694.12
HG No59	50.22	79.33	12515.96
HG No60	50.27	59.71	9429.87
HG No61	50.44	81.57	12925.74
HG No62	50.40	82.64	13084.91
HG No63	50.46	81.90	12983.18
HG No64	47.23	68.80	10208.37
HG No65	47.21	63.28	9385.35
HG No66	47.33	79.03	11751.10
HG No67	47.31	53.10	7892.19
HG No68	47.30	76.83	11416.73
HG No69	47.29	80.95	12026.41
HG No70	47.42	80.01	11919.44
HG No71	47.40	81.49	12134.80
HG No72	36.37	80.22	9165.92
HG No73	36.43	78.48	8981.90
HG No74	36.46	79.39	9093.53
HG No75	36.55	80.93	9292.80
HG No76	36.28	80.54	9179.71
HG No77	36.38	78.03	8918.14
HG No78	31.62	80.06	7952.93
HG No79	32.15	79.82	8062.00
HG No80	31.95	81.32	8162.40
HG No81	32.33	81.28	8255.42
HG No82	47.48	80.06	11941.98
HG No83	47.38	79.20	11788.81
HG No84	47.13	82.21	12172.28
HG No85	47.20	80.11	11878.97
HG No86	47.02	80.79	11934.11
HG No87	46.83	80.00	11769.66
HG No88	46.93	80.52	11871.46
HG No89	47.40	81.21	12093.10
HG No90	47.19	81.12	12026.18
HG No91	47.42	80.58	12004.35
HG No92	47.39	79.07	11771.95
HG No93	47.53	81.33	12144.19
HG No94	47.62	82.41	12328.75
HG No95	47.52	79.73	11902.77
HG No96	47.41	78.91	11753.08
HG No97	47.67	78.75	11793.58
HG No98	47.48	81.21	12113.51
HG No99	47.53	79.78	11912.74
HG No100	47.40	80.59	12000.78
HG No101	47.54	81.27	12137.78
HG No102	47.64	80.83	12097.46

Appendix 5. Thin section log

Visual estimates of quartz, feld and mica under microscope (10x and 40x)
 18 polished thin sections

Lithology	Count	Sample No.
Granite	4	HG87,92,93,97
Sandstone	6	HG06,45,47,54,57,59
Siltstones & mudstones	5	HG10,48,49,65,68
Shale	3	HG07,42,60

Sample No	Grain size	Sorting	Qtz %	Feld %	Mica %	Comment
HG07	VF	well sorted	60	?	35	black lenses, calcite?
HG42	VF	well sorted	50	?	30	black blobs
HG60	VF	well sorted	30	?	40	black patches (weathering?) thinly bedded
HG10	VF	well sorted	60	<10?	30	rounded quartz grains, black blobs (lithic?)
HG48	VF	well sorted	60	?	35	
HG49	VF	well sorted	60	1	35	feld in vein? Q vein?
HG65	VF	well sorted	30	?	20	black grains 15%
HG68	VF	well sorted	40	?	30	black grains 15%
HG06	F	poor sorting	60	<1	35	large rounded quartz grains,
HG45	VF	well sorted	55	5	35	angular rectangular, black grains 5%
HG47	F-M	poor sorting	45	?	45	
HG54	F-M	poor sorting	60	?	35	black grains 1%, clusters of Q grains
HG57	F-M	poor sorting	65	?	25	calcite in veins, rounded
HG59	M-C	poor sorting	60	?	25	Q grains
HG87	C	EQI	50	30	15	
HG92	C	phan	60	20	15	
HG93	VC	phan	65	20	10	very large crystals
HG97	VC	phan	55	20	15	very large crystals, 1cm length

Appendix 6. Magnetic susceptibility and density of samples

Mathinna Group HG01-71 Blue-sandstone Green- mudstones and siltstones
 Granites HG72-102 Pink- shale Orange- granite

Sample No.	Mag Susceptibilty		Dry density		Wet density	
	x10-3	error +-	grams/cm3	error +-	grams/cm3	error +-
HG01	0.067	0.0001	2.68	0.005	2.680	0.005
HG02	0.027	0.0001	2.67	0.005	2.674	0.005
HG03	0.067	0.0001	2.68	0.005	2.685	0.005
HG04	0.060	0.0001	2.69	0.005	2.691	0.005
HG05	0.020	0.0001	2.70	0.005	2.694	0.005
HG06	0.120	0.0001	2.76	0.005	2.757	0.005
HG25	0.040	0.0001	2.71	0.005	2.703	0.005
HG28	0.080	0.0001	2.69	0.006	2.683	0.006
HG44	17.333	0.0001	2.78	0.005	2.785	0.005
HG45	18.333	0.0001	2.78	0.005	2.780	0.005
HG46	14.667	0.0001	2.77	0.005	2.768	0.005
HG47	0.027	0.0001	2.68	0.005	2.683	0.005
HG50	0.020	0.0001	2.68	0.005	2.679	0.005
HG51	0.007	0.0001	2.67	0.004	2.668	0.004
HG52	0.020	0.0001	2.69	0.005	2.690	0.005
HG53	0.007	0.0001	2.67	0.005	2.673	0.005
HG54	0.020	0.0001	2.66	0.005	2.668	0.005
HG55	0.027	0.0001	2.64	0.004	2.642	0.004
HG57	0.053	0.0001	2.68	0.004	2.679	0.004
HG59	0.007	0.0001	2.13	0.004	2.092	0.003
HG61	0.053	0.0001	2.68	0.004	2.679	0.004
HG63	0.073	0.0001	2.69	0.004	2.690	0.004
HG67	0.333	0.0001	2.72	0.007	2.723	0.007
HG71	0.107	0.0001	2.71	0.004	2.707	0.004
HG07	0.133	0.0001	2.77	0.005	2.767	0.005
HG11	0.153	0.0001	2.75	0.005	2.751	0.005
HG12	0.173	0.0001	2.77	0.006	2.764	0.006
HG13	0.160	0.0001	2.76	0.006	2.749	0.006
HG14	0.173	0.0001	2.77	0.005	2.758	0.005
HG15	0.153	0.0001	2.76	0.007	2.759	0.007
HG16	0.140	0.0001	2.76	0.005	2.761	0.005
HG17	0.160	0.0001	2.78	0.009	2.768	0.009
HG18	0.153	0.0001	2.75	0.005	2.738	0.005
HG19	0.167	0.0001	2.78	0.005	2.769	0.005
HG20	0.153	0.0001	2.77	0.005	2.766	0.005
HG22	0.133	0.0001	2.77	0.005	2.762	0.005
HG23	0.187	0.0001	2.78	0.005	2.772	0.005
HG24	0.150	0.0001	2.78	0.006	2.778	0.006
HG27	0.173	0.0001	2.78	0.005	2.773	0.005
HG29	0.187	0.0001	2.81	0.005	2.797	0.005
HG42	0.100	0.0001	2.73	0.004	2.730	0.004
HG60	0.160	0.0001	2.71	0.005	2.729	0.005
HG21	0.093	0.0001	2.74	0.005	2.736	0.005
HG30	0.153	0.0001	2.76	0.006	2.753	0.006
HG65	0.590	0.0001	2.76	0.006	2.761	0.006

Sample No.	Mag Susceptibilty x10-3	error +-	Dry density grams/cm3	error +-	Wet density grams/cm3	error +-
HG68	0.973	0.0001	2.78	0.005	2.782	0.005
HG69	1.000	0.0001	2.78	0.005	2.779	0.005
HG08	0.173	0.0001	2.77	0.005	2.766	0.005
HG09	0.127	0.0001	2.73	0.005	2.726	0.005
HG10	0.167	0.0001	2.75	0.005	2.749	0.005
HG48	0.193	0.0001	2.80	0.005	2.798	0.005
HG49	0.180	0.0001	2.79	0.005	2.794	0.005
HG64	0.513	0.0001	2.76	0.005	2.760	0.005
HG66	0.353	0.0001	2.73	0.005	2.725	0.005
HG56	0.167	0.0001	2.74	0.005	2.747	0.005
HG58	0.147	0.0001	2.77	0.005	2.776	0.005
HG62	0.127	0.0001	2.73	0.004	2.736	0.004
HG70	1.513	0.0001	2.80	0.005	2.792	0.005
HG72	0.027	0.0001	2.59	0.007	2.609	0.007
HG73	0.027	0.0001	2.57	0.007	2.608	0.008
HG74	0.020	0.0001	2.56	0.007	2.610	0.008
HG75	0.033	0.0001	2.58	0.007	2.609	0.007
HG76	0.033	0.0001	2.58	0.007	2.627	0.008
HG77	0.027	0.0001	2.52	0.007	2.585	0.008
HG78	0.020	0.0001	2.52	0.009	2.595	0.010
HG79	0.020	0.0001	2.55	0.009	2.600	0.010
HG80	0.020	0.0001	2.54	0.009	2.599	0.009
HG81	0.020	0.0001	2.56	0.009	2.590	0.009
HG82	0.017	0.0001	2.58	0.004	2.600	0.004
HG83	0.043	0.0001	2.59	0.004	2.607	0.004
HG84	0.037	0.0001	2.60	0.004	2.608	0.004
HG85	0.070	0.0001	2.59	0.004	2.601	0.004
HG86	0.030	0.0001	2.60	0.004	2.605	0.004
HG87	0.023	0.0001	2.59	0.004	2.603	0.005
HG88	0.050	0.0001	2.59	0.004	2.593	0.004
HG89	0.030	0.0001	2.58	0.004	2.588	0.004
HG90	0.037	0.0001	2.58	0.004	2.591	0.004
HG91	0.023	0.0001	2.58	0.004	2.585	0.004
HG92	0.227	0.0001	2.58	0.004	2.583	0.004
HG93	0.037	0.0001	2.59	0.004	2.585	0.004
HG94	0.057	0.0001	2.60	0.004	2.608	0.004
HG95	0.037	0.0001	2.59	0.004	2.594	0.004
HG96	0.010	0.0001	2.54	0.004	2.558	0.004
HG97	0.010	0.0001	2.56	0.004	2.575	0.004
HG98	0.023	0.0001	2.60	0.004	2.612	0.004
HG99	0.023	0.0001	2.59	0.004	2.597	0.004
HG100	0.010	0.0001	2.59	0.004	2.605	0.004
HG101	0.007	0.0001	2.59	0.004	2.584	0.004
HG102	0.030	0.0001	2.57	0.004	2.614	0.004

Appendix 7. Porosity, sonic velocity and electrical resistivity of samples

Mathinna Group HG01-71 Blue-sandstone
 Granites HG72-102 Pink-shale Green- mudstones and siltstones
 Orange- granite

Sample No.	Porosity %	error +-	Sonic Velocity km/s	error +-	Elect Resistivity W m	error +-
HG01	1.29	0.16	5.17	0.03	1886.64	56.69
HG02	0.63	0.16	5.46	0.04	4232.06	123.76
HG03	1.03	0.16	4.97	0.03	2866.09	84.13
HG04	0.46	0.16	5.49	0.04	5943.14	173.30
HG05	0.23	0.16	5.68	0.04	9408.98	280.99
HG06	0.24	0.16	5.67	0.04	5079.51	149.60
HG25	0.47	0.16	4.44	0.03	25776.37	885.01
HG28	0.58	0.20	4.95	0.04	14573.96	487.57
HG44	0.21	0.14	5.34	0.04	19946.33	641.33
HG45	0.21	0.14	5.34	0.04	17683.63	558.87
HG46	0.14	0.14	5.60	0.04	42571.39	1601.39
HG47	0.07	0.14	5.77	0.04	3047198.44	2423925.10
HG50	0.14	0.14	5.63	0.04	173622.53	12034.97
HG51	0.14	0.14	5.73	0.04	66879.66	2912.08
HG52	0.07	0.14	5.79	0.04	3366153.59	2797697.97
HG53	0.07	0.14	5.78	0.04	395244.42	49641.52
HG54	0.72	0.14	5.51	0.04	10624.16	319.82
HG55	0.56	0.14	5.35	0.04	14075.00	432.12
HG57	0.49	0.14	5.53	0.04	3308.03	95.95
HG59	20.04	0.15	2.74	0.01	575.84	21.05
HG61	0.87	0.13	5.58	0.04	1850.11	55.43
HG63	0.56	0.13	4.85	0.03	1947.59	58.02
HG67	0.22	0.22	3.92	0.02	6126.00	217.33
HG71	0.07	0.14	5.61	0.04	25445.40	848.10
HG07	0.40	0.16	5.06	0.03	14708.47	461.24
HG11	0.88	0.16	4.47	0.03	8961.24	270.97
HG12	0.54	0.18	4.26	0.03	28547.92	1023.38
HG13	0.93	0.19	3.66	0.03	21081.33	879.22
HG14	1.21	0.15	4.94	0.03	934.59	29.46
HG15	0.43	0.22	3.51	0.02	65526.30	2943.78
HG16	0.47	0.16	4.21	0.02	26483.86	915.00
HG17	0.91	0.26	3.45	0.03	7722.38	290.02
HG18	1.70	0.16	4.19	0.02	1329.41	41.33
HG19	0.57	0.16	4.08	0.02	38736.67	1465.41
HG20	0.57	0.16	4.31	0.02	26130.33	903.95
HG22	0.84	0.15	3.90	0.06	7191.06	400.52
HG23	0.39	0.16	4.77	0.03	22111.95	736.87
HG24	0.39	0.20	4.62	0.03	18767.70	645.68
HG27	0.57	0.17	4.30	0.02	19461.36	639.52
HG29	0.82	0.15	3.69	0.02	10041.16	305.42
HG42	0.42	0.14	5.23	0.03	10091.67	298.71
HG60	4.07	0.18	4.49	0.03	402.62	19.76
HG21	0.48	0.16	5.03	0.03	21365.35	710.62
HG30	0.46	0.19	4.67	0.03	15258.13	505.35
HG65	0.54	0.18	6.70	0.06	3675.23	119.83

Sample No.	Porosity		Sonic Velocity		Elect Resistivity	
	%	error +-	km/s	error +-	W m	error +-
HG68	0.30	0.15	5.95	0.04	260.78	12.13
HG69	0.71	0.14	5.48	0.04	263.08	11.76
HG08	0.40	0.16	5.14	0.03	11698.00	360.96
HG09	0.24	0.16	5.31	0.04	27873.01	974.15
HG10	0.55	0.16	4.69	0.03	18016.51	580.87
HG48	0.14	0.14	5.48	0.04	591445.84	104995.88
HG49	0.07	0.15	5.35	0.04	221971.34	17719.67
HG64	0.22	0.15	4.49	0.03	14725.37	478.84
HG66	0.22	0.14	3.79	0.03	18973.65	607.52
HG56	1.61	0.15	4.93	0.03	1317.91	40.44
HG58	1.63	0.14	5.21	0.04	972.58	31.47
HG62	0.67	0.12	5.61	0.04	2234.75	65.64
HG70	0.71	0.14	5.09	0.03	3479.98	101.58
HG72	0.24	0.24	5.49	0.04	14226.79	474.09
HG73	0.24	0.24	5.75	0.04	7543.89	232.83
HG74	1.21	0.24	5.15	0.03	882.21	27.19
HG75	0.94	0.24	4.97	0.03	714.14	22.29
HG76	0.72	0.24	4.91	0.03	1123.74	33.71
HG77	0.99	0.25	5.10	0.03	540.65	17.85
HG78	0.48	0.32	5.43	0.04	15224.36	546.32
HG79	0.46	0.31	5.39	0.04	9545.04	311.30
HG80	0.46	0.31	5.18	0.03	17466.56	644.07
HG81	0.75	0.30	5.20	0.03	4943.89	148.92
HG82	0.35	0.14	5.66	0.04	15463.71	481.66
HG83	0.50	0.14	5.75	0.04	7083.46	209.28
HG84	0.35	0.14	5.60	0.04	19229.36	613.22
HG85	0.64	0.14	5.53	0.04	7413.18	218.51
HG86	0.21	0.14	5.71	0.04	19092.77	611.18
HG87	0.36	0.15	5.75	0.04	20455.96	663.97
HG88	0.50	0.14	5.76	0.04	14396.05	445.18
HG89	0.35	0.14	5.52	0.04	4634.86	134.38
HG90	0.28	0.14	5.63	0.04	14108.88	433.95
HG91	1.05	0.14	5.34	0.04	4911.34	142.91
HG92	0.36	0.14	5.89	0.04	15377.21	480.44
HG93	0.34	0.14	5.68	0.04	86338.89	4202.46
HG94	0.20	0.14	5.32	0.04	108032.68	5862.78
HG95	0.14	0.14	5.37	0.04	73709.49	3346.35
HG96	0.99	0.14	5.32	0.04	1218.42	38.33
HG97	0.85	0.14	5.76	0.04	7560.25	224.29
HG98	0.28	0.14	5.70	0.04	13342.66	407.44
HG99	0.56	0.14	5.60	0.04	3114.95	91.42
HG100	0.28	0.14	5.72	0.04	14755.75	456.36
HG101	0.76	0.14	5.57	0.04	14636.39	450.86
HG102	1.46	0.14	5.54	0.04	12083.71	365.75

Appendix 8. Heat capacity and thermal conductivity of samples

Mathinna Group HG01-71 Blue-sandstone Green- mudstones and siltstones
 Granites HG72-102 Pink- shale Orange- granite

Sample No.	Heat capacity		Thermal conductivity	
	J/gK	error +-	W/mK	error +-
HG01	0.59	0.08	4.41	0.221
HG02	0.61	0.08	4.76	0.238
HG03	0.62	0.08	4.14	0.207
HG04	0.63	0.08	4.39	0.219
HG05	0.60	0.08	4.87	0.243
HG06	0.62	0.08	3.63	0.127
HG25	0.62	0.08	4.10	0.205
HG28	0.66	0.09	4.82	0.241
HG44	0.60	0.07	2.66	0.093
HG45	0.62	0.07	2.85	0.100
HG46	0.64	0.07	3.16	0.111
HG47	0.60	0.07	4.69	0.235
HG50	0.65	0.07	5.06	0.253
HG51	0.61	0.07	5.00	0.250
HG52	0.64	0.07	5.26	0.263
HG53	0.64	0.07	5.06	0.253
HG54	0.65	0.07	5.00	0.250
HG55	0.62	0.07	4.95	0.247
HG57	0.63	0.07	4.56	0.228
HG59	0.64	0.09	2.18	0.076
HG61	0.63	0.07	5.14	0.257
HG63	0.61	0.07	4.95	0.248
HG67	0.69	0.10	4.39	0.220
HG71	0.63	0.07	5.08	0.254
HG07	0.64	0.08	3.52	0.123
HG11	0.67	0.08	3.09	0.108
HG12	0.68	0.09	2.28	0.080
HG13	0.66	0.12	2.83	0.099
HG14	0.65	0.08	3.88	0.194
HG15	0.67	0.10	2.65	0.093
HG16	0.65	0.08	2.86	0.100
HG17	0.67	0.11	2.52	0.088
HG18	0.61	0.08	4.05	0.202
HG19	0.63	0.08	2.13	0.075
HG20	0.65	0.08	2.34	0.082
HG22	0.69	0.18	2.12	0.074
HG23	0.65	0.07	2.23	0.078
HG24	0.67	0.09	2.49	0.087
HG27	0.68	0.08	1.99	0.070
HG29	0.66	0.08	1.44	0.051
HG42	0.65	0.07	3.20	0.112
HG60	0.67	0.08	3.10	0.155
HG21	0.63	0.08	5.13	0.257
HG30	0.69	0.09	3.61	0.180
HG65	0.68	0.09	2.86	0.100

Sample No.	Heat capacity		Thermal conductivity	
	J/gK	error +-	W/mK	error +-
HG68	0.68	0.08	3.32	0.116
HG69	0.65	0.07	3.69	0.184
HG08	0.65	0.08	2.93	0.102
HG09	0.64	0.08	3.45	0.172
HG10	0.64	0.08	2.71	0.095
HG48	0.63	0.07	3.20	0.112
HG49	0.65	0.08	3.10	0.108
HG64	0.63	0.07	3.85	0.192
HG66	0.66	0.07	4.14	0.207
HG56	0.67	0.07	2.75	0.096
HG58	0.65	0.07	4.00	0.200
HG62	0.64	0.07	3.47	0.174
HG70	0.66	0.07	2.83	0.099
HG72	0.68	0.13	3.12	0.109
HG73	0.60	0.12	3.21	0.112
HG74	0.66	0.12	3.61	0.126
HG75	0.66	0.12	3.42	0.120
HG76	0.65	0.12	3.74	0.131
HG77	0.66	0.13	3.49	0.122
HG78	0.63	0.16	3.59	0.126
HG79	0.65	0.15	3.42	0.120
HG80	0.67	0.15	3.42	0.120
HG81	0.67	0.15	3.48	0.122
HG82	0.64	0.07	3.34	0.167
HG83	0.64	0.07	3.61	0.180
HG84	0.60	0.07	3.51	0.175
HG85	0.62	0.07	3.45	0.172
HG86	0.63	0.07	3.70	0.185
HG87	0.65	0.07	3.60	0.126
HG88	0.65	0.07	3.16	0.158
HG89	0.62	0.07	3.50	0.175
HG90	0.61	0.07	3.54	0.177
HG91	0.60	0.07	3.80	0.190
HG92	0.61	0.07	3.04	0.106
HG93	0.64	0.07	3.80	0.190
HG94	0.63	0.07	3.35	0.168
HG95	0.65	0.07	3.53	0.176
HG96	0.65	0.08	3.32	0.166
HG97	0.64	0.07	3.25	0.114
HG98	0.63	0.07	3.59	0.179
HG99	0.64	0.07	3.51	0.176
HG100	0.65	0.07	3.58	0.179
HG101	0.63	0.07	3.41	0.171
HG102	0.63	0.07	3.86	0.193

Appendix 9. K%, U ppm and Th ppm of samples
Values from GRS, XRF and LA-ICP-MS

Sample No.	Potassium		Uranium		Thorium		
	%	% error +-	ppm	ppm error	ppm	ppm error	
HG01	1.95	0.45	0.31	8.70	7.95	3.02	Sandstones
HG02	1.14	0.44	0.00	8.89	10.56	2.96	
HG03	1.80	0.44	1.04	8.87	12.37	2.96	
HG04	1.16	0.43	1.28	8.63	12.05	2.88	
HG05	1.27	0.43	1.95	8.65	6.69	2.88	
HG06	2.90	0.43	3.16	8.70	15.55	2.90	
HG25	1.58	0.44	1.40	8.75	9.04	2.92	
HG28	0.98	0.55	0.67	10.92	7.89	3.64	
HG44	3.11	0.38	0.00	7.65	16.21	2.55	
HG45	3.13	0.39	0.00	7.71	19.96	2.57	
HG46	2.92	0.38	1.51	7.67	16.66	2.56	
HG47	1.81	0.40	1.66	7.96	6.57	2.65	
HG50	0.82	0.40	1.63	8.07	8.75	2.69	
HG51	0.46	0.40	0.00	7.94	2.86	2.65	
HG52	0.99	0.40	1.48	8.07	5.83	2.69	
HG53	1.12	0.40	0.18	8.01	6.61	2.67	
HG54	1.37	0.41	1.16	8.11	7.73	2.70	
HG55	1.28	0.40	0.58	8.04	9.55	2.68	
HG57	1.83	0.40	0.00	7.91	8.17	2.64	
HG59	0.92	0.50	2.39	9.93	10.07	3.31	
HG61	1.62	0.35	1.75	6.97	12.97	2.32	
HG63	1.94	0.35	1.76	6.99	7.22	2.33	
HG67	2.67	0.60	3.82	11.95	21.01	3.98	
HG71	1.12	0.39	1.60	7.76	6.41	2.59	
HG07	2.57	0.43	3.04	8.58	12.87	2.86	Shales
HG11	2.82	0.44	0.00	8.80	15.46	2.93	
HG12	2.98	0.49	0.61	9.73	20.63	3.24	
HG13	2.72	0.51	1.43	10.21	15.31	3.40	
HG14	3.33	0.41	1.44	8.30	17.17	2.77	
HG15	3.37	0.58	0.00	11.66	19.90	3.89	
HG16	2.67	0.43	2.57	8.52	16.66	2.84	
HG17	4.51	0.71	0.00	14.18	23.46	4.73	
HG18	3.16	0.45	0.00	8.94	17.58	2.98	
HG19	2.94	0.44	0.00	8.88	16.07	2.96	
HG20	3.01	0.44	0.59	8.80	16.39	2.93	
HG22	2.88	0.41	1.63	8.28	14.56	2.76	
HG23	3.31	0.43	0.00	8.55	19.46	2.85	
HG24	4.32	0.53	4.95	10.65	15.41	3.55	
HG27	3.34	0.44	1.27	8.89	18.40	2.96	
HG29	4.88	0.40	1.05	8.02	22.82	2.67	
HG42	2.50	0.38	1.30	7.63	14.60	2.54	
HG60	5.57	0.47	1.42	9.46	22.51	3.15	
HG21	1.27	0.44	1.04	8.80	5.99	2.93	Mudstones and siltstones
HG30	2.46	0.51	1.34	10.11	12.01	3.37	
HG65	2.93	0.49	2.76	9.85	14.40	3.28	
HG68	3.30	0.40	4.27	8.05	16.17	2.68	
HG69	3.62	0.38	3.64	7.65	14.65	2.55	
HG08	2.82	0.44	0.92	8.71	15.32	2.90	

Sample No.	Potassium		Uranium		Thorium	
	%	% error +-	ppm	ppm error	ppm	ppm error
HG09	2.21	0.44	1.75	8.85	11.90	2.95
HG10	2.78	0.43	2.14	8.67	16.12	2.89
HG48	3.92	0.39	2.58	7.70	18.42	2.57
HG49	3.80	0.40	2.72	7.96	14.81	2.65
HG64	1.78	0.40	1.23	7.93	13.54	2.64
HG66	2.32	0.40	2.48	7.94	11.50	2.65
HG56	4.93	0.40	2.02	8.04	14.97	2.68
HG58	3.86	0.38	0.69	7.69	15.11	2.56
HG62	3.71	0.34	1.08	6.70	16.30	2.23
HG70	3.24	0.38	2.50	7.64	12.64	2.55
HG72	3.80	0.69	19.06	13.74	16.33	4.58
HG73	3.75	0.70	10.70	14.06	18.24	4.69
HG74	3.26	0.70	24.00	13.95	14.41	4.65
HG75	3.38	0.68	36.48	13.62	7.02	4.54
HG76	4.16	0.69	25.03	13.75	12.78	4.58
HG77	3.79	0.72	25.45	14.40	11.82	4.80
HG78	3.96	0.92	16.07	18.42	50.51	6.14
HG79	3.25	0.89	19.46	17.78	54.30	5.93
HG80	5.18	0.89	21.04	17.71	32.06	5.90
HG82	4.00	0.40	10.65	8.10	30.60	2.70
HG83	3.92	0.41	21.21	8.19	30.54	2.73
HG84	4.40	0.40	17.77	7.98	35.51	2.66
HG85	4.14	0.41	9.11	8.22	33.61	2.74
HG86	3.96	0.41	32.93	8.18	27.52	2.73
HG87	4.01	0.42	21.00	8.38	22.93	2.79
HG88	4.39	0.41	18.29	8.26	28.21	2.75
HG89	3.83	0.40	32.96	8.04	30.37	2.68
HG90	4.62	0.41	11.26	8.12	19.75	2.71
HG91	3.81	0.41	38.00	8.15	17.70	2.72
HG92	4.00	0.42	20.39	8.30	26.54	2.77
HG93	4.38	0.40	23.60	7.96	36.63	2.65
HG94	4.49	0.39	8.49	7.80	35.55	2.60
HG95	4.28	0.40	10.95	8.10	33.11	2.70
HG96	4.31	0.42	10.89	8.36	12.53	2.79
HG97	3.89	0.41	81.55	8.27	20.91	2.76
HG98	3.70	0.40	28.92	7.96	21.00	2.65
HG99	3.53	0.41	38.34	8.17	17.74	2.72
HG100	3.84	0.40	31.02	8.07	15.45	2.69
HG101	4.83	0.40	43.88	8.04	14.13	2.68
HG102	4.67	0.40	16.35	8.04	16.89	2.68

Appendix 10. Regression data

Regression results for XRF, LA-ICP-MS and fertiliser data.

Just the Th (in 10-3gms) divided by mass in Kgms to get wt% in ppm

==== Run information ===

Scheme: weka.classifiers.functions.LinearRegression -S 0 -R 1.0E-8

Relation: th

Instances: 20

Attributes: 2

cts Th

Th(10-3gms)

Test mode: 10-fold cross-validation

==== Classifier model (full training set) ===

Linear Regression Model

$$\text{Th}(10-3\text{gms}) = 0.0259 * \text{cts Th} + 0.1467$$

==== Cross-validation ===

==== Summary ===

Correlation coefficient	0.9543
Mean absolute error	0.8122
Root mean squared error	1.0124
Relative absolute error	29.1793 %
Root relative squared error	28.8153 %
Total Number of Instances	20

Uranium (in 10-3gms) divide by mass in Kgms to get wt% in ppm

==== Run information ===

Scheme: weka.classifiers.functions.LinearRegression -S 0 -R 1.0E-8

Relation: u

Instances: 20

Attributes: 3

Nu

Nth

U

Test mode: 10-fold cross-validation

==== Classifier model (full training set) ===

Linear Regression Model

$$U = 0.0153 * \text{Nu} - 0.0096 * \text{Nth} - 0.1697$$

==== Cross-validation ===

==== Summary ===

Correlation coefficient	0.8959
Mean absolute error	1.7733
Root mean squared error	3.0797
Relative absolute error	36.8556 %
Root relative squared error	43.7145 %
Total Number of Instances	20

K content (in gms) divided by weight and times by 100 to get wt%
==== Run information ===

Scheme: weka.classifiers.functions.LinearRegression -S 0 -R 1.0E-8

Relation: K

Instances: 20

Attributes: 4

Nk

Nu

Nth

K

Test mode: 10-fold cross-validation

==== Classifier model (full training set) ===

Linear Regression Model

$K = 0.009 * Nk - 0.0065 * Nu - 0.0047 * Nth - 0.4781$

Time taken to build model: 0 seconds

==== Cross-validation ===

==== Summary ===

Correlation coefficient	0.9888
Mean absolute error	1.2315
Root mean squared error	1.5525
Relative absolute error	18.6704 %
Root relative squared error	15.274 %
Total Number of Instances	20

Appendix 11. Heat generation values for all samples

HP- heat production

Sample No.	K HP		U HP		Th HP		Total HP		
	uW/m ³	error %							
HG01	0.18	0.04	0.08	2.25	0.56	0.21	0.82	2.51	Sandstones
HG02	0.11	0.04	0.00	0.00	0.74	0.21	0.85	0.25	
HG03	0.17	0.04	0.27	2.30	0.87	0.21	1.31	2.55	
HG04	0.11	0.04	0.33	2.25	0.85	0.21	1.29	2.49	
HG05	0.12	0.04	0.51	2.25	0.47	0.21	1.10	2.50	
HG06	0.28	0.04	0.84	2.32	1.13	0.21	2.25	2.58	
HG25	0.15	0.04	0.37	2.29	0.64	0.21	1.16	2.54	
HG28	0.09	0.05	0.17	2.83	0.56	0.26	0.82	3.14	
HG44	0.30	0.04	0.00	0.00	1.19	0.19	1.49	0.23	
HG45	0.30	0.04	0.00	0.00	1.46	0.19	1.76	0.23	
HG46	0.28	0.04	0.40	2.05	1.21	0.19	1.90	2.28	
HG47	0.17	0.04	0.43	2.07	0.46	0.19	1.06	2.29	
HG50	0.08	0.04	0.42	2.09	0.62	0.19	1.12	2.32	
HG51	0.04	0.04	0.00	0.00	0.20	0.19	0.24	0.22	
HG52	0.09	0.04	0.39	2.10	0.41	0.19	0.89	2.33	
HG53	0.10	0.04	0.05	2.07	0.46	0.19	0.62	2.30	
HG54	0.13	0.04	0.30	2.09	0.54	0.19	0.97	2.32	
HG55	0.12	0.04	0.15	2.05	0.66	0.19	0.93	2.28	
HG57	0.17	0.04	0.00	0.00	0.58	0.19	0.75	0.22	
HG59	0.07	0.04	0.48	2.01	0.55	0.18	1.11	2.23	
HG61	0.15	0.03	0.45	1.81	0.91	0.17	1.52	2.00	
HG63	0.18	0.03	0.46	1.82	0.51	0.17	1.15	2.02	
HG67	0.25	0.06	1.01	3.15	1.50	0.29	2.76	3.49	
HG71	0.11	0.04	0.42	2.03	0.46	0.18	0.98	2.25	
HG07	0.25	0.04	0.81	2.30	0.94	0.21	2.00	2.55	Shales
HG11	0.27	0.04	0.00	0.00	1.12	0.21	1.39	0.26	
HG12	0.29	0.05	0.16	2.60	1.50	0.24	1.95	2.89	
HG13	0.26	0.05	0.38	2.72	1.11	0.25	1.75	3.01	
HG14	0.32	0.04	0.38	2.21	1.25	0.20	1.95	2.46	
HG15	0.33	0.06	0.00	0.00	1.44	0.29	1.77	0.34	
HG16	0.26	0.04	0.69	2.28	1.21	0.21	2.15	2.53	
HG17	0.44	0.07	0.00	0.00	1.71	0.35	2.14	0.42	
HG18	0.30	0.04	0.00	0.00	1.27	0.22	1.57	0.26	
HG19	0.29	0.04	0.00	0.00	1.17	0.22	1.46	0.26	
HG20	0.29	0.04	0.16	2.35	1.19	0.22	1.64	2.61	
HG22	0.28	0.04	0.44	2.21	1.06	0.20	1.77	2.45	
HG23	0.32	0.04	0.00	0.00	1.42	0.21	1.74	0.25	
HG24	0.42	0.05	1.33	2.86	1.13	0.26	2.88	3.18	
HG27	0.32	0.04	0.34	2.39	1.34	0.22	2.01	2.65	
HG29	0.48	0.04	0.28	2.17	1.68	0.20	2.44	2.41	
HG42	0.24	0.04	0.34	2.02	1.05	0.18	1.63	2.24	
HG60	0.53	0.05	0.38	2.50	1.62	0.23	2.52	2.77	
HG21	0.12	0.04	0.28	2.33	0.43	0.21	0.83	2.58	Mudstones and siltstones
HG30	0.24	0.05	0.36	2.69	0.87	0.25	1.46	2.99	
HG65	0.28	0.05	0.74	2.63	1.05	0.24	2.07	2.92	
HG68	0.32	0.04	1.15	2.17	1.18	0.20	2.65	2.41	
HG69	0.35	0.04	0.98	2.06	1.07	0.19	2.40	2.28	
HG08	0.27	0.04	0.25	2.33	1.11	0.21	1.63	2.59	

Sample No.	K HP		U HP		Th HP		Total HP	
	uW/m ³	error %						
HG09	0.21	0.04	0.46	2.33	0.85	0.21	1.53	2.59
HG10	0.27	0.04	0.57	2.30	1.17	0.21	2.00	2.56
HG48	0.38	0.04	0.70	2.08	1.36	0.19	2.44	2.31
HG49	0.37	0.04	0.74	2.15	1.09	0.20	2.20	2.39
HG64	0.17	0.04	0.33	2.12	0.98	0.19	1.48	2.35
HG66	0.22	0.04	0.65	2.09	0.82	0.19	1.70	2.32
HG56	0.47	0.04	0.54	2.14	1.08	0.20	2.09	2.37
HG58	0.37	0.04	0.19	2.06	1.10	0.19	1.66	2.29
HG62	0.35	0.03	0.29	1.77	1.17	0.16	1.81	1.97
HG70	0.32	0.04	0.68	2.06	0.93	0.19	1.92	2.29
HG72	0.35	0.06	4.81	3.48	1.12	0.32	6.27	3.86
HG73	0.34	0.07	2.70	3.55	1.25	0.33	4.29	3.94
HG74	0.30	0.06	6.06	3.54	0.99	0.32	7.34	3.92
HG75	0.31	0.06	9.20	3.46	0.48	0.31	9.99	3.84
HG76	0.38	0.06	6.36	3.51	0.88	0.32	7.62	3.89
HG77	0.34	0.07	6.36	3.62	0.80	0.33	7.51	4.01
HG78	0.36	0.08	4.03	4.64	3.45	0.43	7.84	5.15
HG79	0.30	0.08	4.89	4.49	3.71	0.42	8.90	4.99
HG80	0.47	0.08	5.29	4.47	2.19	0.41	7.95	4.96
HG82	0.36	0.04	2.68	2.04	2.09	0.19	5.13	2.27
HG83	0.36	0.04	5.35	2.07	2.09	0.19	7.80	2.30
HG84	0.40	0.04	4.48	2.02	2.44	0.19	7.32	2.24
HG85	0.38	0.04	2.29	2.07	2.30	0.19	4.97	2.30
HG86	0.36	0.04	8.30	2.07	1.89	0.19	10.54	2.30
HG87	0.37	0.04	5.29	2.12	1.57	0.19	7.22	2.35
HG88	0.40	0.04	4.58	2.08	1.92	0.19	6.91	2.31
HG89	0.35	0.04	8.25	2.03	2.07	0.19	10.66	2.25
HG90	0.42	0.04	2.82	2.04	1.35	0.19	4.59	2.26
HG91	0.34	0.04	9.50	2.05	1.20	0.19	11.05	2.28
HG92	0.36	0.04	5.09	2.08	1.80	0.19	7.26	2.31
HG93	0.40	0.04	5.90	2.00	2.49	0.18	8.79	2.22
HG94	0.41	0.04	2.14	1.97	2.44	0.18	4.99	2.19
HG95	0.39	0.04	2.75	2.04	2.26	0.19	5.40	2.26
HG96	0.39	0.04	2.69	2.07	0.84	0.19	3.92	2.30
HG97	0.35	0.04	20.31	2.09	1.42	0.19	22.07	2.32
HG98	0.34	0.04	7.30	2.02	1.44	0.18	9.09	2.24
HG99	0.32	0.04	9.63	2.07	1.21	0.19	11.16	2.29
HG100	0.35	0.04	7.81	2.05	1.06	0.19	9.22	2.27
HG101	0.44	0.04	10.96	2.03	0.96	0.18	12.36	2.25
HG102	0.43	0.04	4.13	2.04	1.16	0.19	5.72	2.26

Appendix 12 Glossary of terms

Thermal conductivity- ‘a measure of the ability of a material to conduct heat’ (Kearey 2001), a measure of how easily a quantity of heat propagates through a material (Beardsmore and Cull 2001; Gun et al. 2005).

Thermal diffusivity- ‘the ratio of thermal conductivity to the product of density and specific heat, the rate of heat propagation through a material ’ (Kearey 2001), a physical property, a measure of how quickly or the speed of temperature moves through a material (Beardsmore and Cull 2001).

Thermal gradient/ geothermal gradient- ‘the rate of temperature change with distance’ (Geller 2003).

Steady state methods- involves applying heat (or a constant thermal gradient) over the entire rock sample (Beardsmore and Cull 2001; Midttymme & Roaldset 1999).

Transient methods- involves applying heat at a point or a line in a rock sample or borehole (Midttymme & Roaldset 1999).

Anisotropy- ‘the presence of a preferred orientation’ (Kearey 2001).

Heat generation- generation of heat from mantle and crustal sources, decay from radioactive isotopes is the dominant source (Beardsmore and Cull 2001)

Surface heat flow- heat flow from the crust and mantle rising to the surface (Beardsmore and Cull 2001)

Basal heat flow- heat flow in the basement rocks (Beardsmore and Cull 2001)

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