Recent Developments in the Measurement of Down-Hole Temperatures and Thermal Conductivity for Heat Flow Determination: a Review

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ABSTRACT

Heat flow data are fundamental to almost every Enhanced Geothermal System (EGS) exploration program in Australia. In the absence of direct temperature data from deep petroleum wells, the extrapolation of heat flow data provides one of the only techniques that is able to remotely sense the presence of buried anomalous heat.

Collecting heat flow data can be expensive with bores drilled specifically for heat flow determination (typically 300 m to 1000 m in depth) having a total drilling cost of between AUD$100,000 and AUD$1,000,000.

Exploration boreholes are typically slim 'minerals style' holes with a combination of open-hole and coring techniques used to obtain desired rock samples. Thermal conductivity of the intersected geological section is estimated using laboratory measurements of core or cuttings or by analysis of wireline proxies. Temperature data are collected down-hole using a wireline probe and are either manually recorded at regular intervals (typically every metre) or continuously recorded with a digital data logger. Temperature and thermal conductivity data are used to calculate a single heat flow value or to identify and quantify variations in heat flow with depth. Heat flow data and downward-modelled thermal conductivity values are then used to extrapolate temperature models to target EGS temperatures (typically around 200 °C) at between 3 km and 6 km depth. This large extrapolation is sensitive to the accuracy and inherent uncertainties of heat flow estimates.

Borehole heat flow determinations equate to the regional heat flow if the following assumptions are met:

- Temperatures measured in the bore are only a function of the surface temperature, the basal heat flow and the thermal conductivity of the rock mass under investigation;
- Modelled thermal conductivity accurately reflects the actual thermal conductivity of the rock mass; and
- Heat flows along a path normal to the Earth's surface.

In practice all three of these assumptions are likely to be invalid to varying degrees. Numerous factors influence both temperature and thermal conductivity measurement that must be taken into consideration when calculating heat flow. In recent years there have been a number of significant investigations concerned with improving estimates of crustal temperatures (e.g. Cermak et al., 2007; Vosteen et al., 2006), thermal conductivities of rocks (e.g. Popov et al., 1999a; Vosteen and Schellschmidt 2003; Goutorbe et al., 2006; Mattsson, 2007) and heat flow (e.g. Popov et al., 1999b;

Zschocke et al., 2005b). A selection of the findings from these studies are discussed with respect to EGS exploration objectives.

TEMPERATURE PROFILES

Inherent instability

Temperatures were continuously monitored in two boreholes in Kamchatka (Russia) by Cermak et al. (2007). The authors noted that the temperature intermittently oscillated by several hundredths of a degree over all observable timescales (from a few minutes to several days; Figure 1). This oscillation was attributed to inherent instability in the borehole due to the temperature gradient (i.e. intra-borehole convection) and thermo-structural complexity of the rocks surrounding the bore

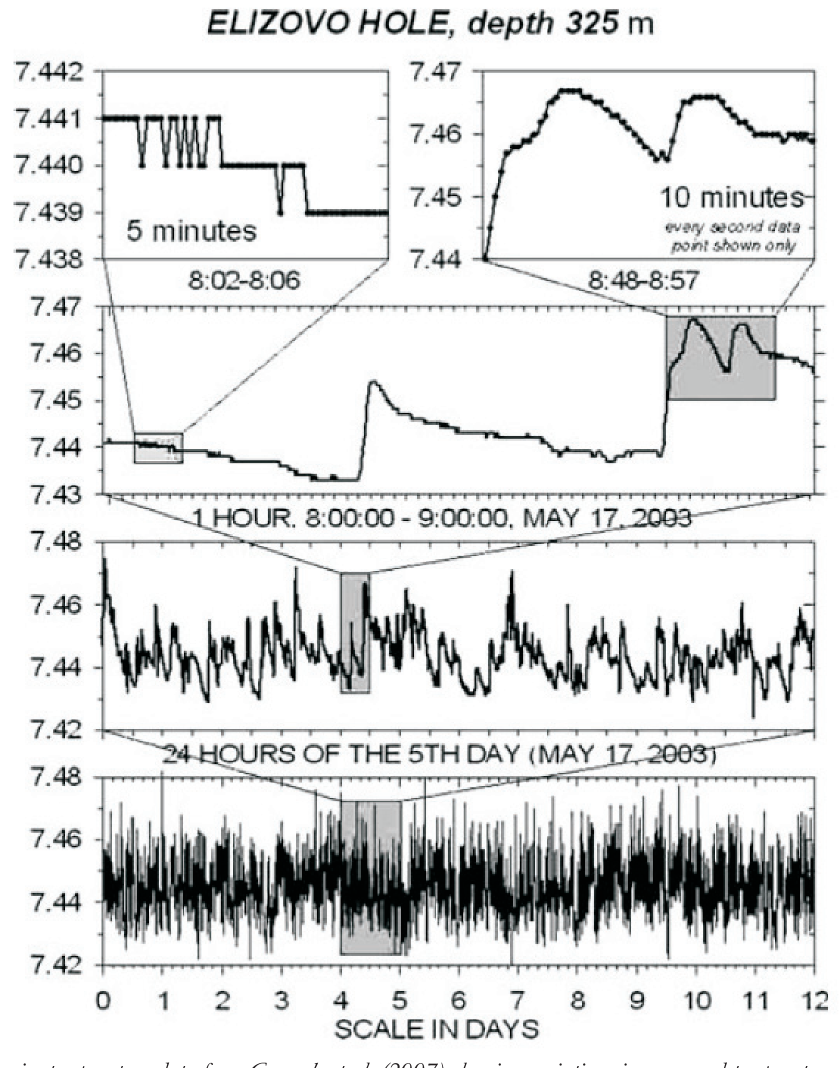

Figure 1. Time series temperature data from Cermak et al. (2007) showing variations in measured temperature of several hundredths of a degree over several timescales.

wall. These findings suggest that care should be taken when measuring borehole temperatures with high resolution temperature sensors and that longer measurement times (>5 minutes) may remove the effect of inherent instability in the temperature profile.

Surface and Palaeoclimatic Effects

Variations in surface temperature due to seasonal and palaeoclimatic change have the potential to cause significant deviations in measured temperature profiles with respect to the steady-state geothermal gradient. The effect of transient palaeotemperatures on temperature profiles in the

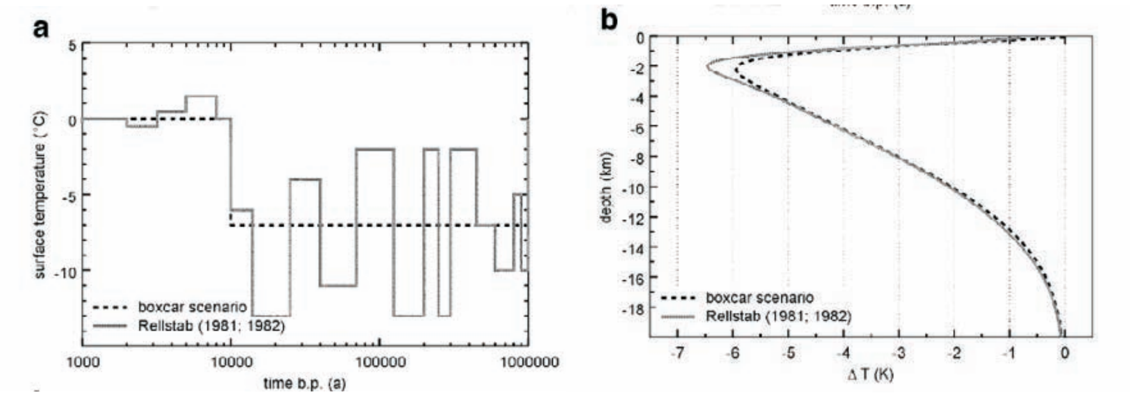

Figure 2. Palaeoclimatic signal calculated from two palaeoclimatic models for the central Alps (Vosteen et al., 2005).

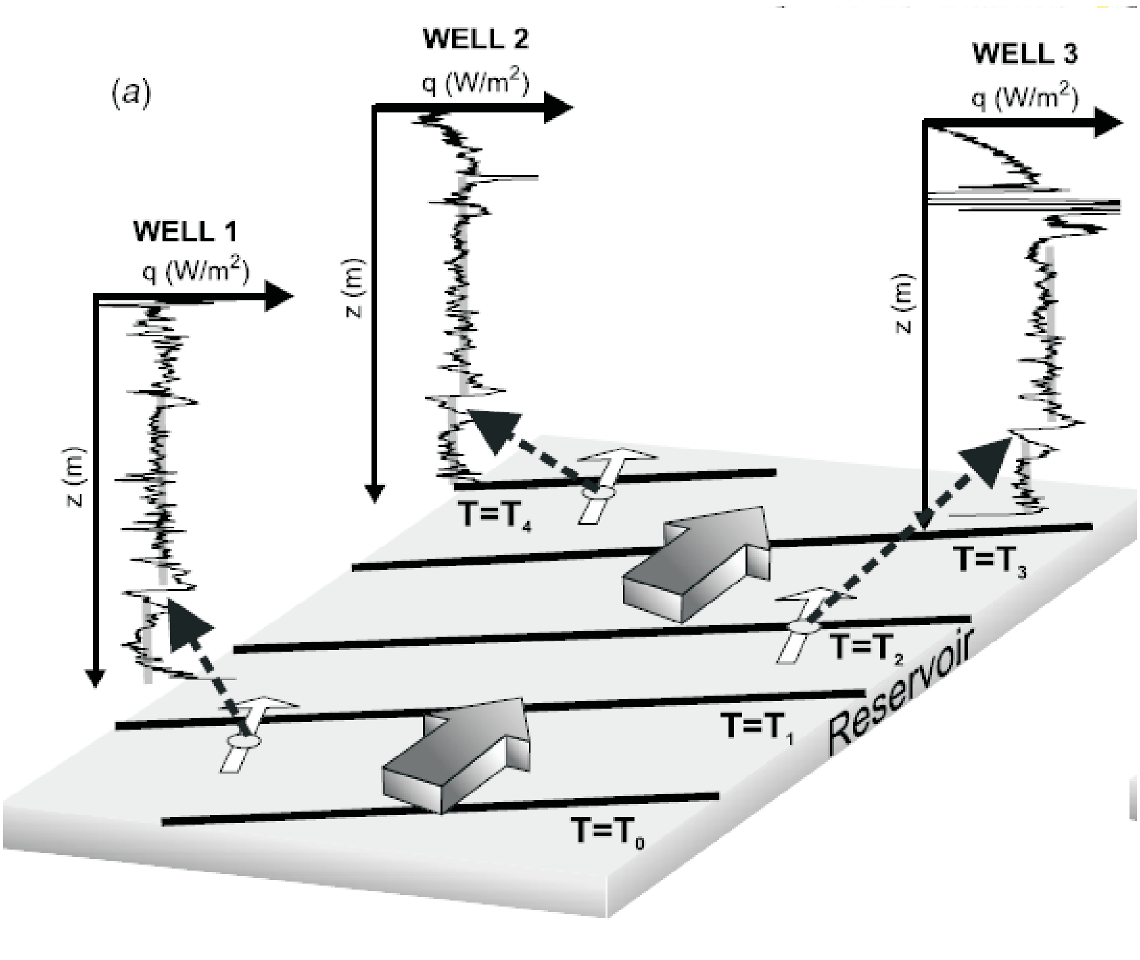

Figure 3. fluid flow model used to explain observed heat flow variations in German boreholes (Zschocke, 2005b).

Tauern Window of the Central Alps has been modelled by Vosteen et al. (2006; Figure 2). The results of a 1D finite difference model, where surface temperatures were 7°C cooler between 10,000 and 1,000,000 years B.P., indicated a maximum perturbation of the steady-state geotherm at 2,000 m depth. The perturbation diminished downwards and could be effectively neglected at 20 km depth. This result implies that temperatures that are uncorrected with respect to variations in paleoclimate may significantly underestimate the steady-state geothermal gradient used for heat flow determinations and temperature extrapolations.

Heat advection

Heat advection due to fluid flow within permeable rocks can also cause significant excursions in the temperature profile and geothermal gradient measured in boreholes. The effect of fluid flow on the steady-state geotherm can be analysed with respect to the Péclet number (the ratio of conductive heat transfer). For large Péclet numbers there is a large positive increase in the observed temperature profile (Zschocke, 2005b). Variations in calculated down-hole heat flow density have been interpreted by several authors as evidence of fluid flow (e.g. Zschocke et al., 2005b; Mottaghy, 2005). For example, Zschocke et al. (2005b) correlated vertical heat flow anomalies across a series for three wells from the Alpine Molasse Basin to estimate the rates of fluid flow within a sub-horizontal aquifer (Figure 3). Variation in down-hole heat flow density had a consistent signature between three wells and could be related to a known dipping aquifer. The thermal conductivity of the sediments was known from laboratory analysis. This allowed the authors to determine that the heat flow perturbation was too large to be due to changes in the thermal conductivity alone and advection of heat was a likely source of the anomalously low values at depth (Zschocke et al., 2005b).

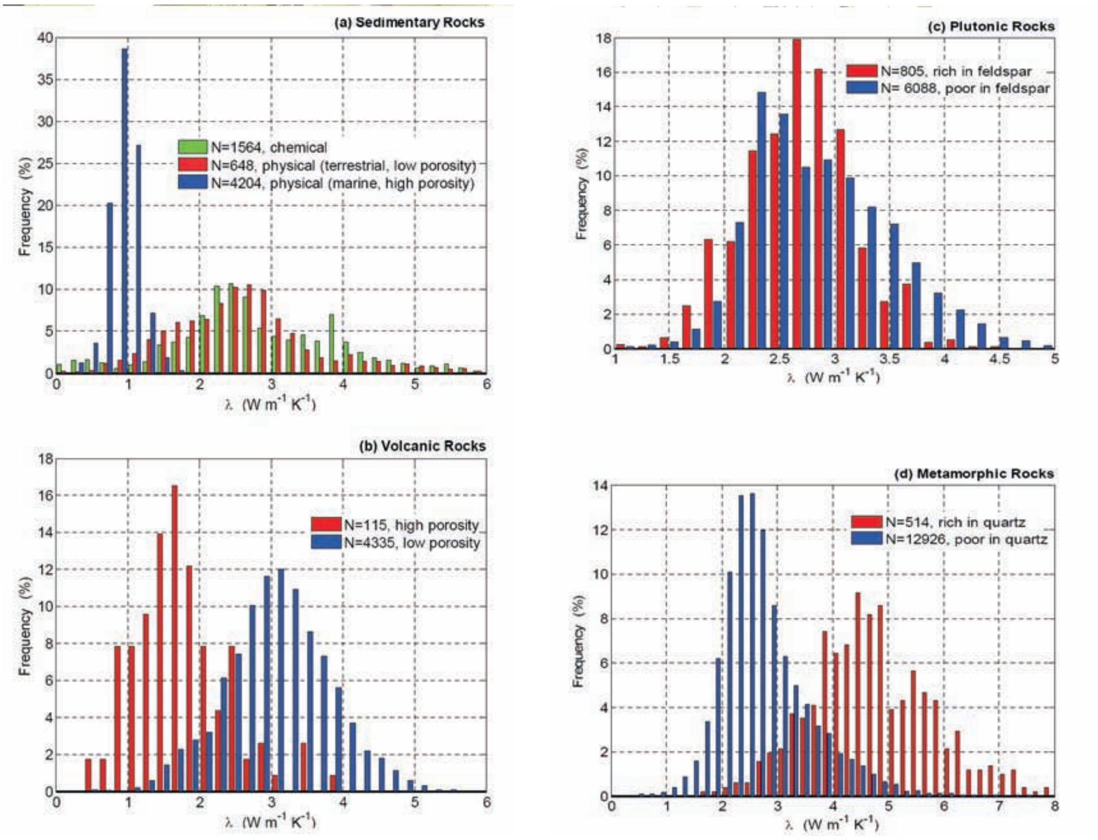

Figure 4. Frequency histograms of thermal conductivity values for various rock types (Data from Hartmann cited in Clauser, 2006).

Time Series Temperature Measurement

Multi-sensor thermistor arrays (e.g. the Seistronix TL-300 Borehole Temperature Logger) can be used to instantaneously measure the down hole temperature over a useful depth range (e.g. 200 m). Measurements can be made periodically permitting time series analysis of temperature variations. Thermal diffusivity, thermal conductivity, the effect of advection and palaeotemperatures can all be modelled by analysing the rates of change of the temperature field following a thermal perturbation (e.g. circulation during drilling; Zschocke, 2005a).

THERMAL CONDUCTIVITY

A detailed review of the thermal conductivity of rocks and minerals can be found in Clauser and Huenges (1995) and more recently in Clauser (2006). Figure 4 shows measured thermal conductivities for a range of rock types.

Wireline proxies

Cores are usually taken to provide laboratory thermal conductivity samples. However, coring is expensive (approximately 30 % to 50 % of drilling cost). Rock cuttings are cheaper to procure and may be used to determine matrix thermal conductivity and then corrected if rock porosity data are available (Clauser, 2006 and references therein). Due to drilling processes (e.g. abrasion during drilling and transport) it is common for particular lithologies (e.g. mudstones, coals, and shales) to be poorly represented in recovered core and cuttings (Williams and Anderson, 1990). Furthermore, there is often significant uncertainty as the exact depth of sampled drill cuttings due to lag times of the circulating drill mud. In such situations, wireline measurements (where available) may provide the best source of lithological and down-hole ambient data.

Several empirical methods have been suggested that use petrophysical wire line proxies to estimate thermal conductivity. Most methods use some combination of sonic, gamma, bulk density, and neutron density and use multi-component mixing laws to determine the thermal conductivity models (comprehensively discussed in Hartmann et al., 2005 and Clauser, 2006). Many of these methods have shown good correlation with laboratory measured thermal conductivity values for similar geological samples; however, due to the empirical derivation of these studies no method has yet been developed that is applicable to global datasets (Clauser, 2006).

Artificial Neural Networks

Goutorbe et al. (2006) developed a protocol for using neural networks to predict thermal conductivities from wireline logs. The authors compared their neural network protocol to a conventional mixing law proxy (described in Hartmann et al., 2005) and found that they achieved better correlation for ODP site863B. They quoted an accuracy of around 15 % which is comparable to other empirical methods (Clauser, 2006). The authors argued that their neural network method is more robust and objective than conventional mixing law calculations and should be applicable to a diverse range of geological materials (Goutorbe et al., 2006).

Optical scanning technology

Optical scanning of rock slabs and core is a novel, non-destructive method for determining the thermal conductivity (and thermal diffusivity) of geological samples (Popov et al., 1999a and 1999b). The method uses a constant laser heat source combined with two infra-red sensors (one in series and one parallel to the source) that track at uniform speed along the desired sample profile (Figure 5). This versatile method can be applied to the three dimensional study of sample anisotropy. The results of optical scanning show good correlation with both line-source and divided

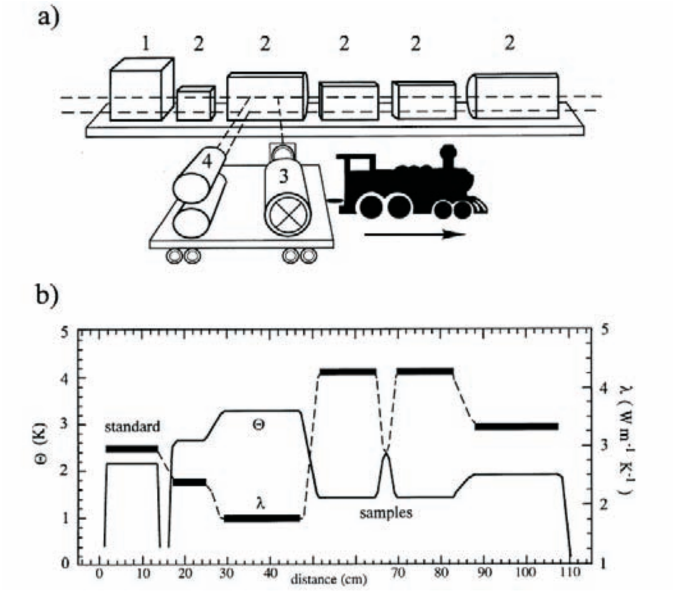

Figure 5. Analytical setup for optical scanning analysis of various samples (Popov et al., 1999a).

bar thermal conductivity determinations (Popov et al., 1999a). Yuri Popov is currently working on a device that will reliably measure smaller samples and possibly cuttings (*pers. comm.*).

Thin section analysis

Analyses of cores and crushed samples from the 4 km deep KTB hole (Germany) by Pribnow and Umsonst (1993) indicated strong links between thermal conductivity, mineralogy and fabric development. These authors found that in metamorphic rocks quartz had an overriding control on the magnitude of thermal conductivity while sheet silicates were largely responsible for measured anisotropy. Previous work on thin section determination of thermal conductivity is reviewed in Drury and Jessop (1983). They found models that used aggregate values derived from known mineral thermal conductivities yielded results that were within ±15 % of laboratory-measured values. The results of Pribnow and Umsonst (1993) and Drury and Jessop (1983; and authors discussed therein) allow the possibility that mineral volume data combined with porosity data and fabric analysis of samples (via thin section analysis) may be used to make estimates of the thermal conductivity of core (and possibly cuttings) from exploration drill holes.

In-Situ Thermal Response Testing

In-situ thermal response testing is used to characterise the averaged thermal properties of boreholes. A fluid of known elevated temperature is pumped through a coupled u-tube heat exchanger that is inserted into the entire length of the bore hole (Mattsson, 2007). The temperature of the outgoing fluid is then measured as is the amount of heat required to maintain the injection temperature. These tests yield an average value of thermal conductivity along the entire length of the hole. Thermal response testing has been developed to service the needs of the direct use geothermal industry (Mattsson, 2007), but the technology could easily be scaled up for use in EGS exploration.

Portable Divide Bar Apparatus

A drawback of convention steady-state thermal conductivity measurement has been that the equipment required has been too heavy and power intensive to be used in the field. A new highly portable divided bar apparatus has been developed by Hot Dry Rocks Pty Ltd for use in the field

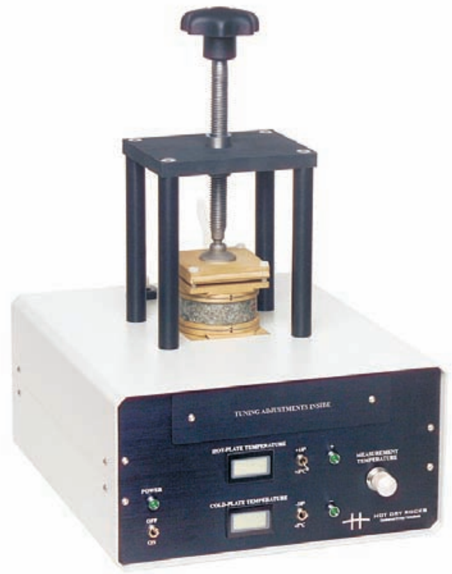

Figure 6. Portable divided bar apparatus from Hot Dry Rocks Pty Ltd.

(Figure 6). This device has the advantage that the samples can be analysed for thermal conductivity at the drill site shortly after sampling, so long as some basic core preparation facilities are at hand. Field measurement of this kind could potentially reduce the magnitude of errors which may occur as a result of dehydration (and rehydration) of the sample (as is common practice for laboratory analysis).

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