GEOSCIENCE AUSTRALIA

Australian Government
Geoscience Australia

Heat Flow Determinations for the Australian Continent: Release 2

Jones, T.D.; Kirkby, A.L.; Gerner, E.J.; Weber, R.D.

Record
2011/28
GeoCat #
71773

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Heat Flow Interpretations for the Australian Continent: Release 2

GEOSCIENCE AUSTRALIA
RECORD 2011/28

by

Jones, T.D.[1], Kirkby, A.L.[1], Gerner, E.J.[1], and Weber, R.[1]

Australian Government
Geoscience Australia

1. Geoscience Australia

Department of Resources, Energy and Tourism
Minister for Resources and Energy: The Hon. Martin Ferguson, AM MP
Secretary: Mr Drew Clarke

Geoscience Australia
Chief Executive Officer: Dr Chris Pigram

ISSN 1448-2177
ISBN 978-1-921954-252

GeoCat # 71773

Bibliographic reference:

Jones, T.D., Kirkby, A.L., Gerner, E.J., and Weber, R.D. Heat flow determinations for the Australian Continent: Release 2. Geoscience Australia Record 2011/28, 24pp

Contents

Executive Summary

The understanding of Australia's geothermal resources is based on limited data such as temperature measurements taken in petroleum and mineral boreholes across the country. Heat flow studies are rarer, with existing publicly available compilations containing less than 150 heat flow data-points for Australia. Both temperature and heat flow data are unevenly distributed and, where no data exist, the available information has been interpolated over large areas to generate national-scale maps.

This report presents temperature, natural gamma and thermal conductivity data for seven boreholes, four from the Eastern Goldfields region of Western Australia, and three from the Lake Frome region of South Australia. Temperature logging was performed down hole with temperatures recorded at 20 cm intervals. Drill core samples were taken from each well and measured for thermal conductivity by Geoscience Australia.

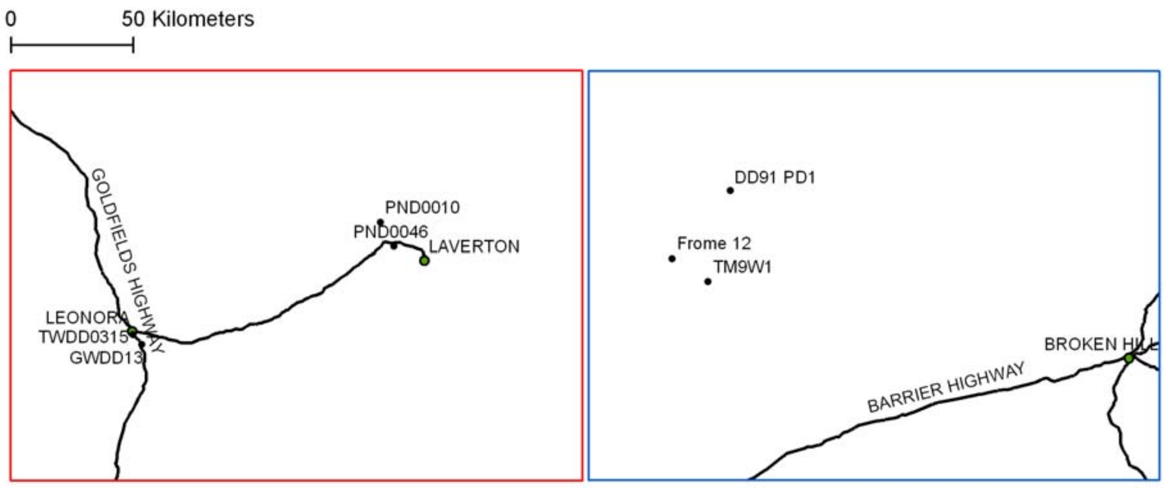
One dimensional conductive heat flow models have been produced for six of the seven wells presented here. For the Eastern Goldfields regions, heat flow values ranging from 23 – 36 mW/m^2 were determined. These low values are consistent with existing heat flow data in the broad region. For the Lake Frome region, values of 79 – 103 mW/m^2 have been determined, also consistent with existing data in the broad region.

Introduction

Geoscience Australia (GA) has been improving the coverage of heat flow determinations across the Australian continent, as part of the Federal Government funded Onshore Energy Security Program. Previously collected heat flow data are sparse and unevenly distributed. The acquisition of heat flow data is useful to the geothermal industry, as it helps highlight areas that may be worthy of more detailed exploration. Heat flow data can also help constrain crustal depth and composition models. These can then be used to run thermal models allowing temperatures to be predicted at depth, away from actual measurements.

Geoscience Australia began thermal logging of boreholes across Australia in late 2008 and as of June 2011 has collected 168 temperature logs. In late 2009, the thermal conductivity meter became operational, allowing the project to begin thermal conductivity measurements of samples collected from logged boreholes.

This study presents new data which adds to the database of heat flow determinations across Australia. Data from seven boreholes were collected in two regions and were chosen due to their availability for logging. These regions are the Eastern Goldfields region of Western Australia and the Lake Frome region of South Australia. The locations are shown in Figure 1, and the results are summarised in Appendix 1.



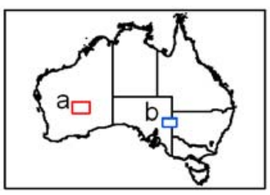


Figure 1. *Top left panel*; map of Eastern Goldfields region, Western Australia, showing the location of boreholes PND0010, PND0046, GWDD13 and TWDD0315. *Top right panel*; map of Lake Frome region, South Australia, showing the locations of boreholes DD91 PD1, Frome 12, TM9W1. *Bottom left panel*; map of Australia showing the location of panels presented above.

Data Collection

TEMPERATURE LOGS

Temperature logging of the holes was undertaken by Geoscience Australia using an Auslog A626 combined temperature/natural gamma probe. The probe has a temperature precision of 0.007 °C and an upper temperature limit of 70 °C. The logging winch holds 1800 m of four-conductor cable, sufficient to log all holes presented in this study to full depth or to where the holes were blocked. Communication with the tools and data recording was through an Auslog DLS5 digital logging system connected to a laptop computer. Data was continuously recorded downwards into the hole at a speed of approximately five metres per minute at a logging interval of 20 cm. Once collected, the temperature logs were converted from measured depth (logged distance along drill hole) to true vertical depth using drillhole azimuth and dip information, and smoothed using a three point running mean. The raw temperature logs (as .las files) can be found in Appendix 2.

UNCERTAINTY IN TEMPERATURE LOGS

Heat generated within the Earth is radiated at the surface at rates in the order of tens of mW/m^2. In comparison, heat is received at the surface by radiation emitted by the sun at rates of up to 1000 W/m^2 (Cull and Sparksman, 1977). Climatic perturbations will, therefore, affect near surface temperature readings. Seasonal, diurnal, and longer period changes in solar activity are a source of transient fluctuations in surface temperature. Furthermore, topography will affect near surface temperature readings. To avoid these effects, temperatures are usually taken below a cut-off depth at which these effects are insignificant, for the purposes of heat flow modelling.

The thermal conditions of the borehole should ideally, be in equilibrium with the surrounding rock. This ensures that the measured temperature is an accurate representation of the undisturbed subsurface temperature. The process of drilling disturbs the thermal state of the borehole and, therefore where possible, holes were left to equilibrate. Approximately 10-20 times the drilling time is required prior to temperature logging for the borehole to reach equilibrium to within the accuracy of most equipment (Bullard, 1947). Apart from the Frome 12 bore, which due to logistical constraints was logged within 24 hours of drilling, all other readings were taken a minimum of one year after drilling was completed. Therefore, it is very likely that all the boreholes presented in this study (with the exception of Frome 12) would have reached equilibrium by the time they were logged.

Surface heat flow was calculated assuming steady-state, one dimensional (vertical) heat conduction. Although methods exist to remove convective effects on temperature logs, their complexity and need for additional information made them impractical to implement for this study. While it is beyond the scope of this study to expand on these methods, sufficient references exist that explore them in detail (e.g. Hales, 1937; Horton & Rodgers, 1945).

THERMAL CONDUCTIVITY MEASUREMENTS

Core specimens were collected from each hole in order to perform thermal conductivity measurements. Where possible, core samples approximately 15 cm in length were collected at intervals of approximately 50-100 m down each hole. The length of sample and exact interval was dependant on lithological variation and core availability. Where available, lithology logs were used to guide sampling. In addition, temperature and gamma logs were inspected prior to core sampling to ensure samples were collected in areas where there was little varation in the logs.

Each sample was cut and polished into small discs ~15 mm thick and 25 mm in diameter (up to four discs per sample). Discs were oriented so that thermal conductivity was measured in the direction of the long axis of the core, and were cut with the faces parallel. Discs were evacuated under a > 95 % vacuum for at least three hours and were then submerged in water prior to returning to atmospheric pressure. Discs were left in water at atmospheric pressure for a minimum of twelve hours, and remained in water until just prior to conductivity measurement. The thermal conductivity of each disc was measured by Geoscience Australia using an Anter 2022 guarded heat flow thermal conductivity meter. The thermal conductivity of each sample is calculated as the harmonic mean of the disc measurements, and the uncertainty is given as the standard deviation of the measurements. All samples were measured at a temperature of 30 ± 2 °C. The results are presented in this report, and in spreadsheet form in Appendix 3.

Heat Flow Modelling

Heat flow determinations were made using the following method (after Kirkby and Gerner, 2010);

1. A depth interval interpreted to represent near steady-state conductive heat flow was selected from the temperature log, avoiding the near surface parts of the log likely to be affected by transient seasonal effects, and also any sections with indication of being influenced by significant advective flow. The top of the selected interval was taken to be the surface for the purposes of 1D heat flow modelling. In some cases it was necessary to exclude large portions of the hole to select only a near steady-state conductive section of the log.

2. Thermal conductivity values and depth information were inspected to determine which values correspond to the conductive section of the temperature log.

3. The near steady-state conductive section of the hole was divided into sub-sections to coincide with the thermal conductivity values. Boundaries between sub-sections were determined based on significant changes in the natural gamma signal and temperature gradient.

Two methods of heat flow modelling were utilised to determine the final value for heat flow. Given the data for each borehole, the method of Kirkby and Gerner (2010) was sufficient for the majority of heat flow determinations and is presented below:

4. Thermal conductivity values and depths defining the extent of each sub-section were entered into a 1D conductive heat flow modelling spreadsheet. Modelling was started at the top of the near steady-state conductive section, using the measured temperature at that point. Starting from this point, the spreadsheet used the measured thermal conductivities and the sub-section boundaries assigned above, together with an initial estimated heat flow value for the hole, to model the temperature at the base of each thermal conductivity section.

5. The modelled temperatures were plotted against the measured temperature log. The magnitude of the heat flow value in the model was then adjusted until the modelled temperatures best matched the measured temperature log.

6. Finally, error bounds were calculated to provide an indication of the confidence in each heat flow determination. There is error due to the standard deviation on the thermal conductivity values, and also due to the sub-section boundaries picked (described in bullet point 3). To take into account both of these sources of error, upper bound and lower bound heat flow values were calculated for each of the drillholes.
    a. First, boundaries were reassigned to make sections with high thermal conductivity values as thick as possible (resulting in lower heat flow). The heat flow was then determined based on a best fit between the data and the temperature profile predicted from the thermal conductivity values plus one standard deviation. The resulting value is the lowest heat flow that could be matched to the data using the method described in points 1-5.
    b. Boundaries were then reassigned to make the sections with lower thermal conductivity values as thick as possible (resulting in a higher heat flow). The heat flow was determined based on a best fit to the data using the temperature profile predicted from the thermal conductivity values minus one standard deviation. The resulting value is the highest heat flow that could be matched to the data using the method described in points 1-5.

c. The error is then the difference between the initial heat flow determined (in point 5) and the highest and lowest heat flow values determined as per 6a and 6b.
d. In cases where there was a lithological log available for the hole, and there was at least one thermal conductivity measurement for each of the dominant lithologies, the boundaries were not shifted as in 6a and 6b. Instead, the error bounds were calculated using only the thermal conductivity data.

During the modelling stage it was apparent that for boreholes GWDD13 and TWDD0315, a constant value for heat flow would not fit the measured temperature data. In these cases, the sampling interval for thermal conductivity measurements may be too large to accurately represent changes in the thermal conductivity, or alternatively, the heat flow may vary with depth in the borehole. For these boreholes an alternate method below was applied to determine heat flow.

In this alternate method a unique value for heat flow was assigned for each thermal conductivity interval rather than a constant value over the entire borehole. The value at each interval was adjusted until the modelled temperatures matched the logged temperature data. The final value for heat flow and its error is given as the harmonic mean and standard deviation of these values respectively.

Results

This section presents the results of heat flow modelling at each of the seven borehole locations on the basis of steady-state, 1D heat conduction (Table 1).

Table 1. Information and the heat flow determined for each borehole

Borehole ID	Region	Latitude GDA 94	Longitude GDA 94	Logged distance (m)	Dip angle from horizontal (°)	Heat flow mW/m^2	Error on heat flow
GWDD13	Leonora, WA	-28.93136	121.36676	1300	-75	29^	5
TWDD0315	Leonora, WA	-28.89506	121.33435	788	-73	23^	7
PND0010	Laverton, WA	-28.48658	122.23844	554	-65	N/A*	N/A*
PND0046	Laverton, WA	-28.57503	122.28965	505	-87	36	5
DD91 PD1	Lake Frome, SA	-31.35000	140.00301	404.5	-85	79	8
Frome 12	Lake Frome, SA	-31.59777	139.78969	1052.5	-90	103+	+19/-4
TM9W1	Lake Frome, SA	-31.68200	139.92064	578.6	-90	80	3

^Heat flow determined using the second method outlined in the previous section
*Heat flow not determined due to an unstable thermal gradient
+Heat flow determination based on an un-equilibrated thermal gradient

EASTERN GOLDFIELDS REGION

GWDD13

Borehole GWDD13 is located in the Eastern Goldfields region, Western Australia, approximately 5 km southeast of Leonora (Figure 1). It was drilled by St Barbara Limited several years prior to logging.

Visual inspection of the measured temperature log shows that above 250 m true depth the gradient is disturbed. The heat flow determination is therefore, based only on data below this point.

The second method described in the Heat Flow Modelling section was used to determine heat flow for this borehole. The measured temperatures and depths at which core samples were taken are presented in Figure 2a. Table 2a shows the thermal conductivities measured for each sample and the depth interval assigned to each sample.

The calculated heat flow for GWDD13 is to be 29 ± 7 mW/m^2. Interval heat flows are presented in table 2b. The measured and modelled temperature data versus depth are plotted in Figure 2b.

Table 2a. *Summary of sample information for GWDD13 including thermal conductivity and depth interval*

Sample Name	Lithology	Sample Depth (m)	Section Top (m)	Section Bottom (m)	Number of Discs	Thermal Conductivity (W/mK)	Standard Deviation (W/mK)
StBarbLe/8	schist	99	-	-	3	3.88	0.11
StBarbLe/9	diorite	202	-	-	3	2.77	0.06
StBarbLe/10	dolerite	301	250	320	3	2.81	0.11
StBarbLe/11	schist	399	320	450	3	2.36	0.15
StBarbLe/12	schist	498	450	550	3	1.97	0.08
StBarbLe/13	migmatite	599	550	665	3	2.32	0.30
StBarbLe/14	dolerite	749	660	770	3	2.45	0.14
StBarbLe/15	dolerite	848	770	910	3	2.90	0.05
StBarbLe/16	dolerite	949	910	1080	3	5.16	0.58
StBarbLe/17	migmatite	1111	1080	1200	4	3.30	0.22
StBarbLe/18	dolerite	1205	1200	1230	3	2.56	0.05
StBarbLe/19	dolerite	1299	1230	1300	2	2.80	0.09

Table 2b. *Interval boundaries and interval heat flow values determined for GWDD13*

Sample Name	Section Top (m)	Section Bottom (m)	Interval Heat flow (mW/m^2)
StBarbLe/10	250	320	25
StBarbLe/11	320	450	25
StBarbLe/12	450	550	25
StBarbLe/13	550	665	25
StBarbLe/14	660	770	23
StBarbLe/15	770	910	33
StBarbLe/16	910	1080	43
StBarbLe/17	1080	1200	38
StBarbLe/18	1200	1230	35
StBarbLe/19	1230	1300	35

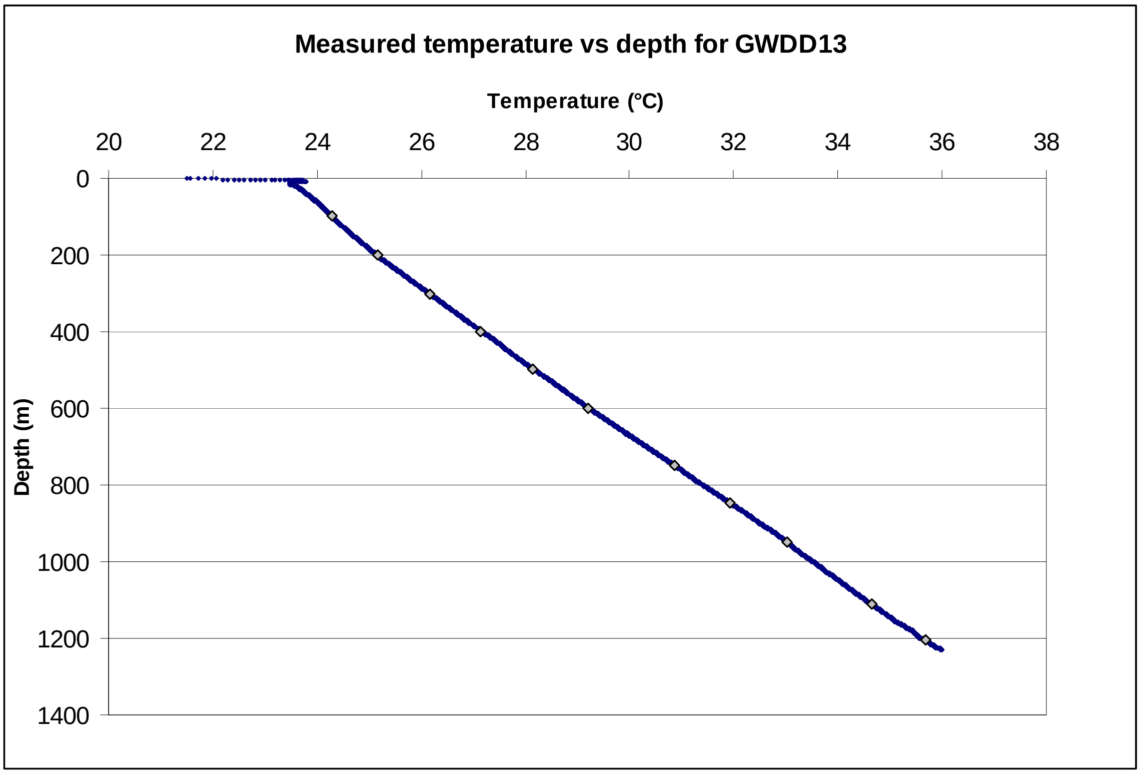


Figure 2a. *Measured temperatures (line) for borehole GWDD13. The depths at which thermal conductivities were measured are marked (diamonds).*

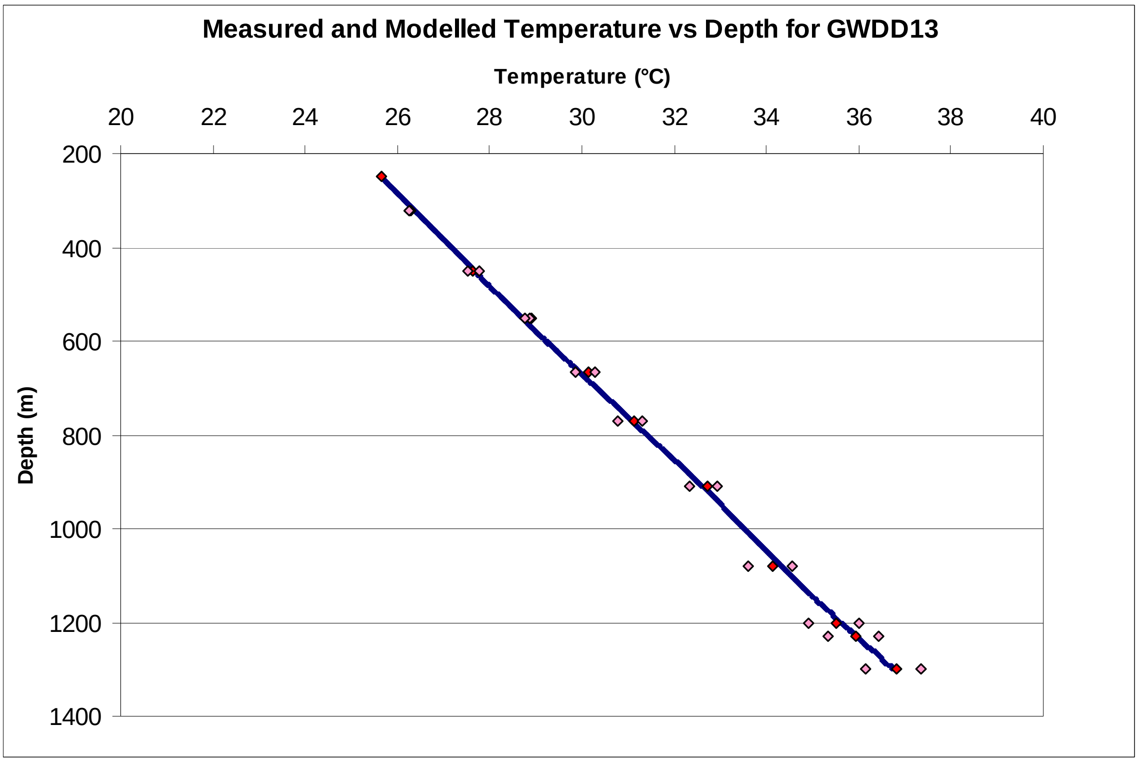


Figure 2b. *Measured temperatures (blue line) for borehole GWDD13. The modelled temperatures for the base of each thermal conductivity section (red diamonds) and the error bounds for each predicted temperature (pink diamonds) are shown..*

TWDD0315

Borehole TWDD0315 is located in the Eastern Goldfields region of Western Australia, approximately 1 km south of Leonora (Figure 1). It was drilled by St Barbara Limited several years prior to logging.

Visual inspection of the measured temperature log shows that above 400 m true depth the gradient is disturbed. Therefore our heat flow determination is based only on data below this point.

The second method described in the Heat Flow Modelling section was used to determine heat flow for this borehole. The measured temperatures and depths at which core samples were taken are presented in Figure 3a. Table 3a shows the thermal conductivities measured for each sample and the depth interval assigned to each sample.

The calculated heat flow for TWDD0315 is 23 ± 7 mW/m^2. Interval heat flows are presented in Table 3b.The measured and modelled temperature data versus depth are plotted in Figure 3b.

Table 3a. *Summary of sample information for TWDD0315 including thermal conductivity and depth interval.*

Sample Name	Lithology	Sample Depth (m)	Section Top (m)	Section Bottom (m)	Number of Discs	Thermal Conductivity (W/mK)	Standard Deviation (W/mK)
StBarbLe/1	dolerite	158	-	-	3	2.29	0.10
StBarbLe/2	altered mudstone	249	-	-	3	2.56	0.20
StBarbLe/3	schist	340	-	-	3	3.16	0.09
StBarbLe/4	diorite	430	400	475	3	2.34	0.05
StBarbLe/5	mafic rock	519	475	575	3	2.61	0.21
StBarbLe/6	diorite	616	575	709	3	2.69	0.12
StBarbLe/7	migmatite	709	708	750	3	3.99	0.63

Table 3b. *Interval boundaries and interval heat flow values determined for TWDD0315*

Sample Name	Section Top (m)	Section Bottom (m)	Interval Heat flow (mW/m^2)
StBarbLe/4	400	475	19
StBarbLe/5	475	575	21
StBarbLe/6	575	709	24
StBarbLe/7	709	750	34

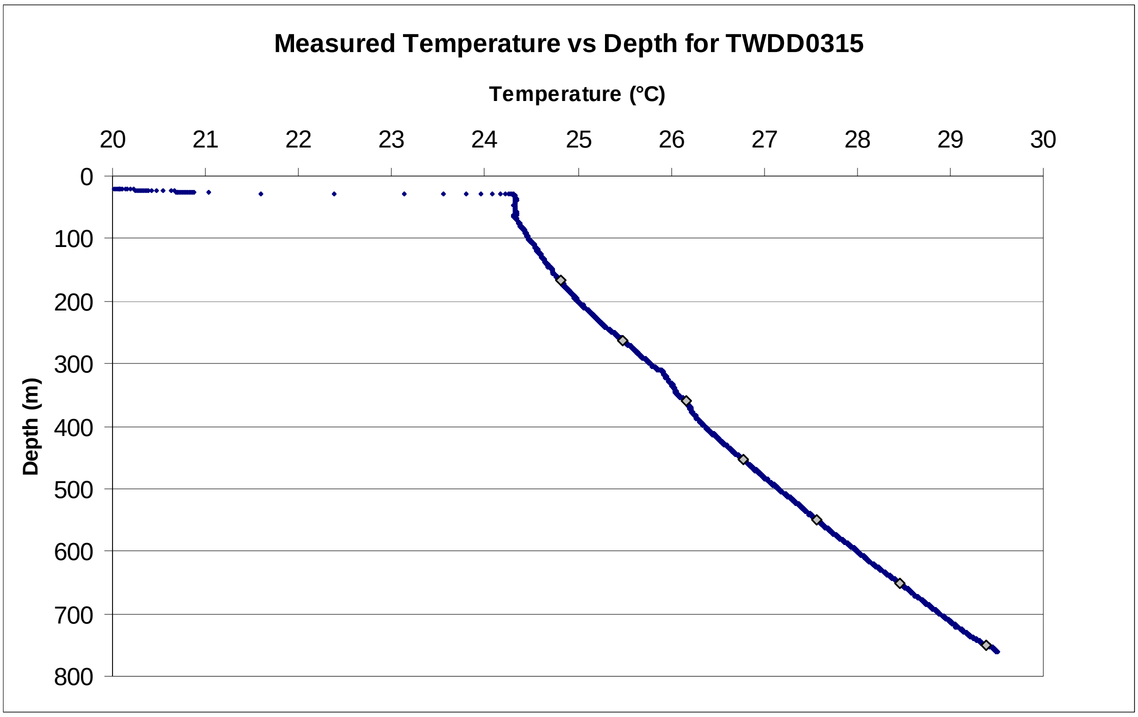


Figure 3a. *Measured temperatures (line) for borehole TWDD0315. The depths at which thermal conductivities were measured are marked (diamonds).*

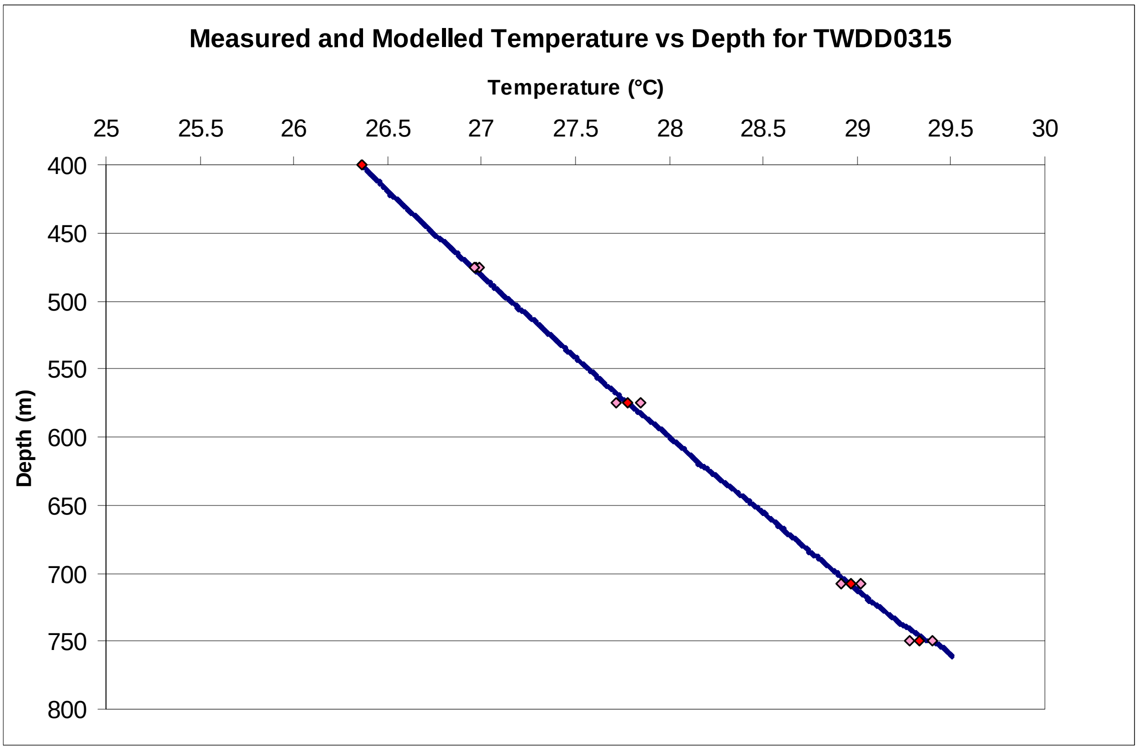


Figure 3b. *Measured temperatures (blue line) for borehole TWDD0315. The modelled temperatures for the base of each thermal conductivity section (red diamonds) and the error bounds for each predicted temperature (pink diamonds) are shown..*

PND0010

PND010 is located in the Eastern Goldfields region of Western Australia, approximately 20 km northwest of Laverton (Figure 1) and was drilled by Poseidon Nickel Limited in May 2007. It was logged by GA in May 2010.

Visual inspection of the measured temperature log shows significant disturbance over the entire borehole. The variation along the log was interpreted as not due to conductive only heat flow. We are therefore, unable to provide a realistic 1D heat flow model for PND010.

Table 4 shows the thermal conductivities for each sample. The measured temperature data versus depth are plotted in Figure 4.

Table 4. *Summary of sample information for PND010 including thermal conductivity and depth interval*

Sample Name	Lithology	Sample Depth (m)	Number of Discs	Thermal Conductivity (W/mK)	Standard Deviation (W/mK)
PosLav/6	mafic intrusive	101.3	3	2.63	0.04
PosLav/7	felsic intrusive	266.1	3	3.18	0.02
PosLav/8	tuff	531.4	4	2.52	0.11

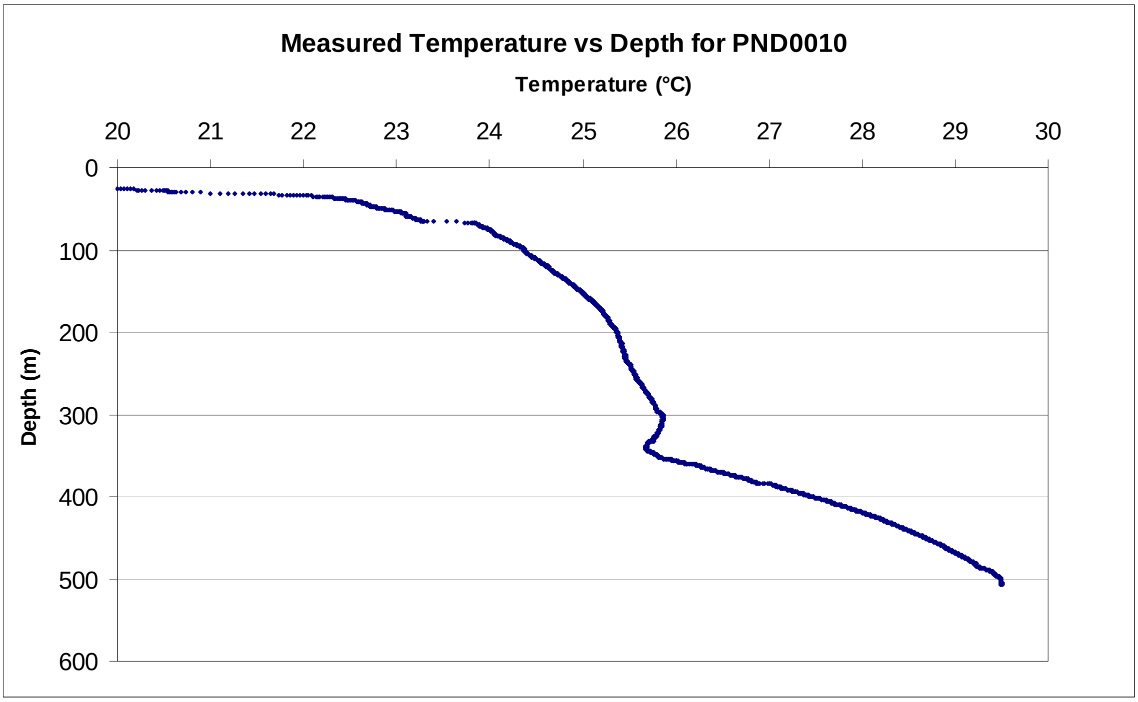


Figure 4. *Measured temperatures (line) versus depth for borehole PND0010.*

PND0046

Borehole PND0046 is located in the Eastern Goldfields region of Western Australia, approximately 10 km west-northwest of Laverton (Figure 1) and was drilled by Poseidon Nickel Limited in September 2008. It was logged by GA in May 2010.

Visual inspection of the measured temperature log shows that above 350 m true depth the gradient is disturbed. Our heat flow determination is based only on data below this point.

The first method described in the Heat Flow Modelling section was used to determine heat flow for this borehole. The measured temperatures and depths at which core samples were taken are presented in Figure 5a. Table 5 shows the thermal conductivities measured for each sample and the depth interval assigned to each sample.

The calculated heat flow for PND0046 is 36 ± 5 mW/m^2. The measured and modelled temperature data versus depth are plotted in Figure 5b.

Table 5. *Summary of sample information for PND0046 including thermal conductivity and depth interval*

Sample Name	Lithology	Sample Depth (m)	Section Top (m)	Section Bottom (m)	Number of Discs	Thermal Conductivity (W/mK)	Standard Deviation (W/mK)
PosLav/1	mafic intrusive	98	-	-	3	2.27	0.15
PosLav/2	chert	374	350	377	4	3.95	2.09
PosLav/3	dolerite	384	377	390	3	2.09	0.15
PosLav/4	mafic intrusive	392	390	407	3	2.13	0.04
PosLav/5	mafic intrusive	473	407	500	3	2.51	0.16

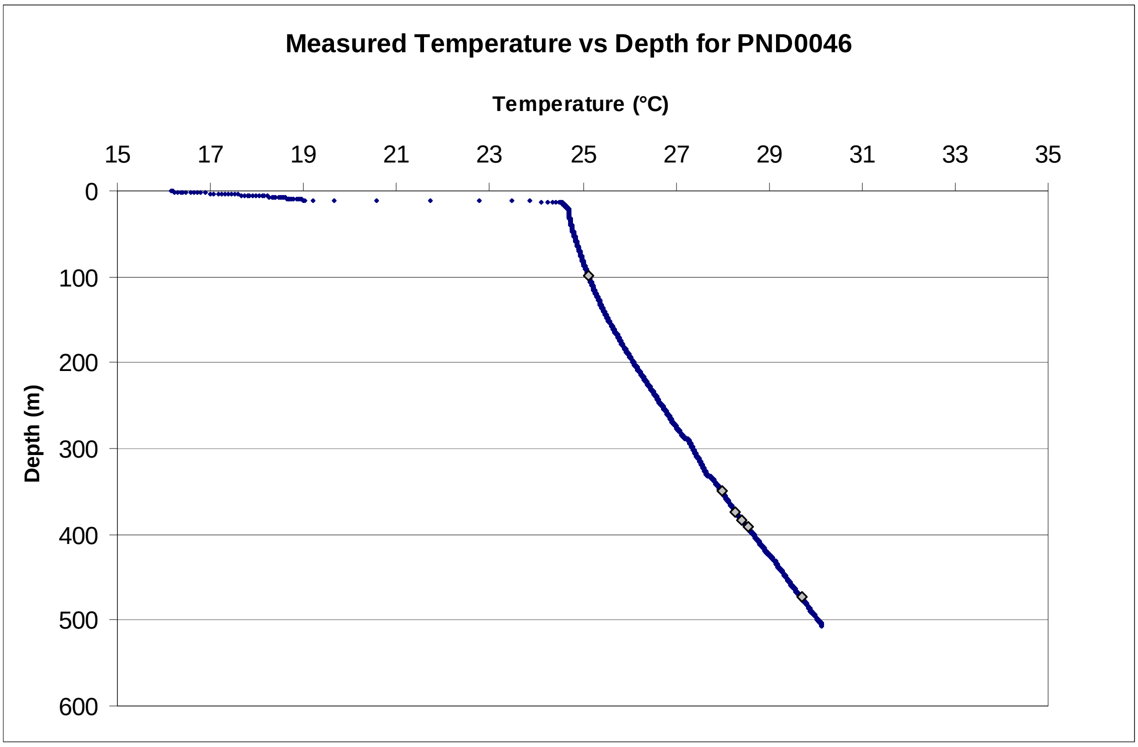


Figure 5a. *Measured temperatures (line) for borehole PND0046. The depths at which thermal conductivities were measured are marked (diamonds).*

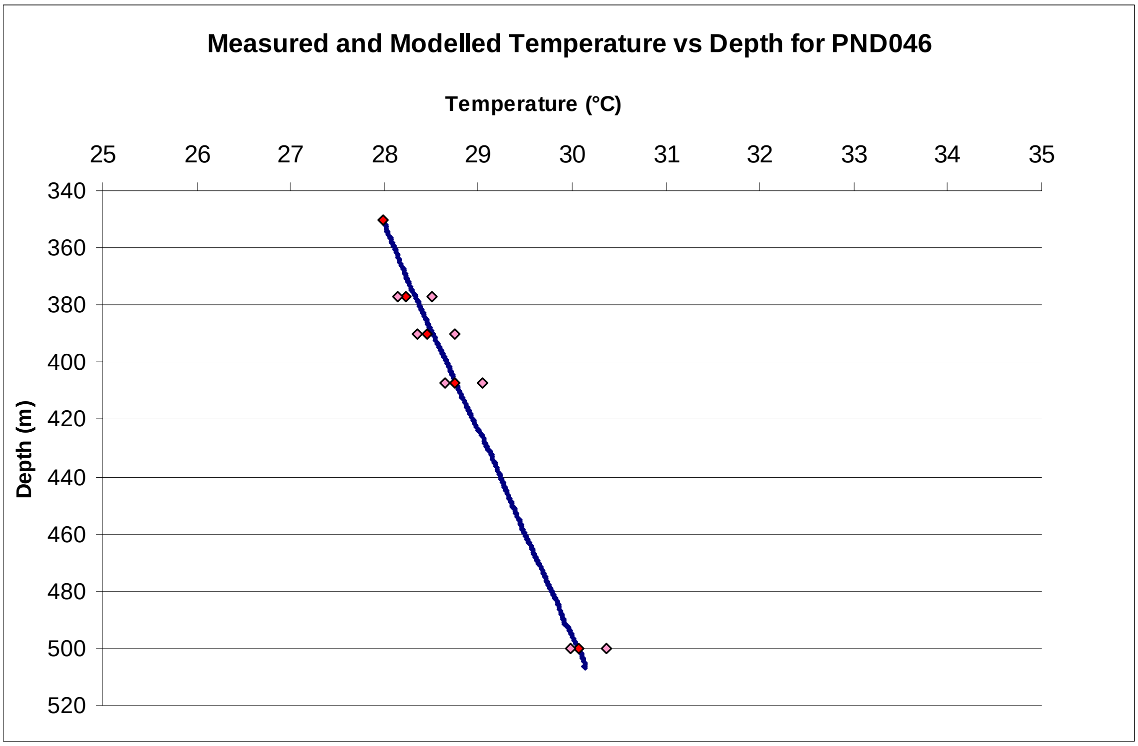


Figure 5b. *Measured temperatures (blue line) for borehole PND0046. The modelled temperatures for the base of each thermal conductivity section (red diamonds) and the error bounds for each predicted temperature (pink diamonds) are shown.*

LAKE FROME REGION

DDP91 PD1

Borehole DDP91 PD1 is located in the Lake Frome region, South Australia, approximately 175 km northwest of Broken Hill (Figure 1) and was drilled by CRA Exploration. It was logged by GA several years after drilling.

Visual inspection of the measured temperature log shows that above 275 m true depth the gradient is disturbed. The heat flow determination is based only on data below this point.

The measured temperatures and depths at which core samples were taken are presented in Figure 6a. Table 6 shows the thermal conductivities measured for each sample and the depth interval assigned to each sample.

The calculated heat flow for DDP91 PD1 is 79 ± 8 mW/m^2. The measured and modelled temperature data versus depth are plotted in Figure 6b.

Table 6. *Summary of sample information for DDP91 PD1 including thermal conductivity and depth interval*

Sample Name	Lithology	Sample Depth (m)	Section Top (m)	Section Bottom (m)	Number of Discs	Thermal Conductivity (W/mK)	Standard Deviation (W/mK)
Pioneer/1	siltstone	142	-	-	2	2.43	0.12
Pioneer/2	siltstone	259	-	-	-	-	-
Pioneer/3	siltstone	294	290	310	2	2.04	0.36
Pioneer/4	siltstone	320	310	329	2	1.97	0.03
Pioneer/5	siltstone	380	329	386	1	2.21	-
Pioneer/6	siltstone	400	386	405	1	1.76	-

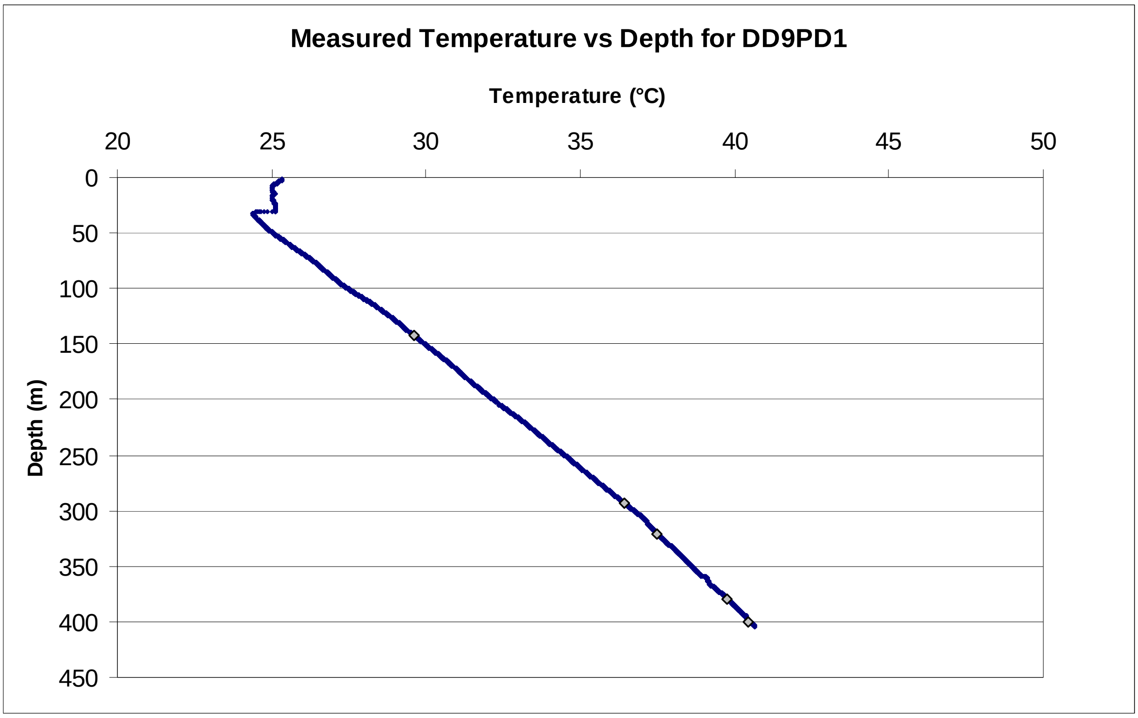


Figure 6a. *Measured temperatures (line) for borehole DD9PD1. The depths at which thermal conductivities were measured are marked (diamonds).*

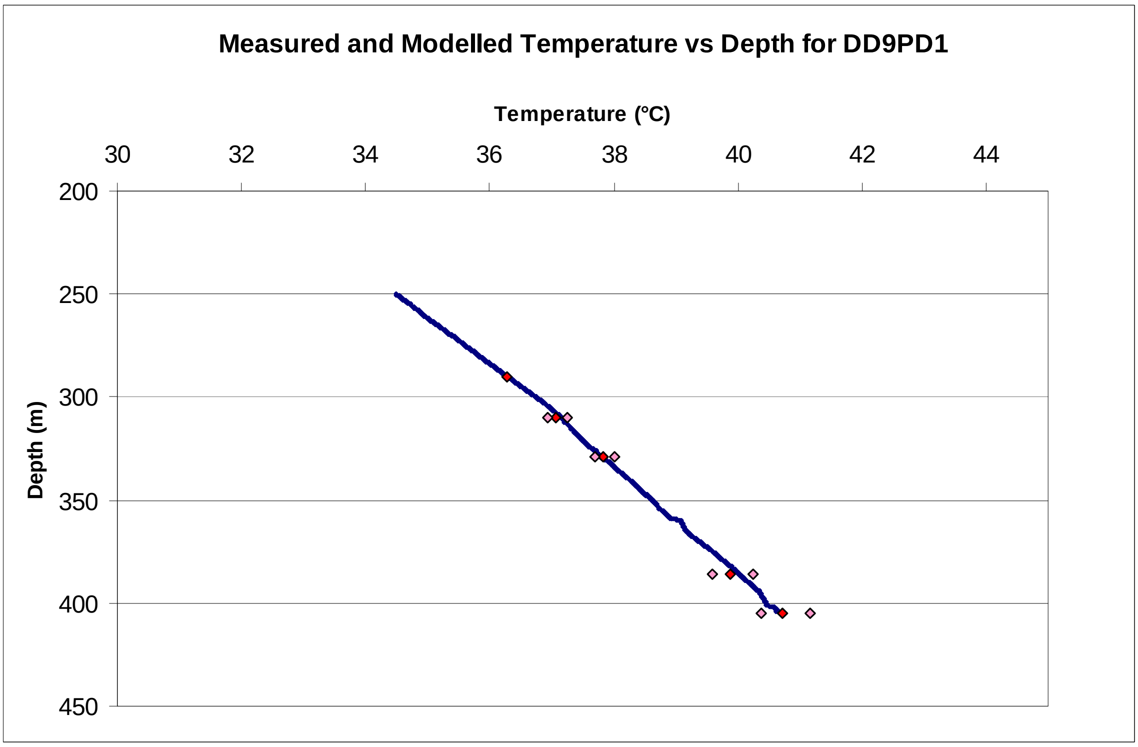


Figure 6b. *Measured temperatures (blue line) for borehole DD9PD1. The modelled temperatures for the base of each thermal conductivity section (red diamonds) and the error bounds for each predicted temperature (pink diamonds) are shown.*

Frome 12

Borehole Frome 12 is located in the Lake Frome region, South Australia, approximately 190 km west-northwest of Broken Hill (Figure 1) and was drilled by Geothermal Resources Limited. It was logged by GA within 24 hours of drilling and would therefore have been unequilibrated when logged.

Visual inspection of the measured temperature log shows that above 275 m true depth the gradient is disturbed. Therefore our heat flow determination is based only on data below this point.

The measured temperatures and depths at which core samples were taken are presented in Figure 7a. Table 7 shows the thermal conductivities measured for each sample and the depth interval assigned to each sample. Sample From/5 was collected at a depth beyond which temperature data was collected and thus was not used in the final heat flow determination.

The calculated heat flow for Frome 12 is 103 (+19/-4) mW/m^2. This heat flow is based on the un-equilibrated temperature log for Frome 12. The measured and modelled temperature data versus depth are plotted in Figure 6b.

Table 7. *Summary of sample information for Frome 12 including thermal conductivity and depth interval*

Sample Name	Lithology	Sample Depth (m)	Section Top (m)	Section Bottom (m)	Number of Discs	Thermal Conductivity (W/mK)	Standard Deviation (W/mK)
From/1	siltstone	335	300	405	2	2.53	0.05
From/2	dolomitic - siltstone	583	405	950	2	2.35	0.10
From/3	chert	963	950	1020	2	3.11	0.13
From/4	siltstone	1045	1020	1050	2	2.13	0.01
From/5	siltstone	1187	N/A*	N/A*	2	2.52	0.06

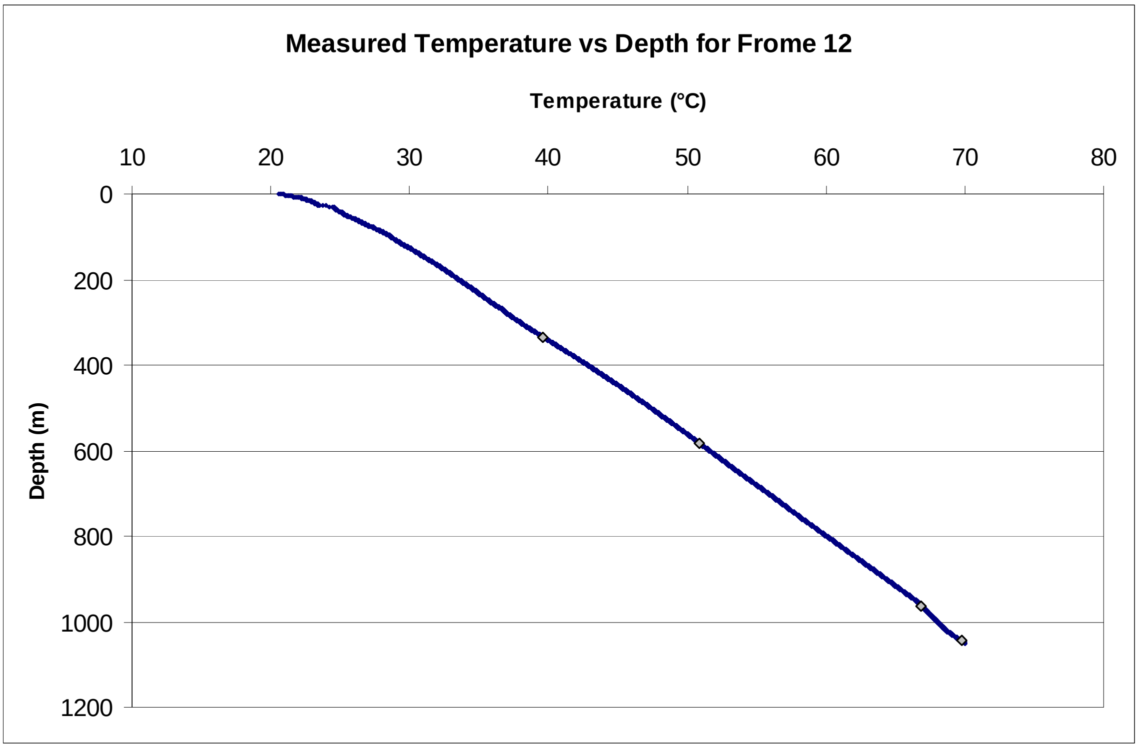


Figure 7a. *Measured temperatures (line) for borehole Frome 12. The depths at which thermal conductivities were measured are marked (diamonds).*

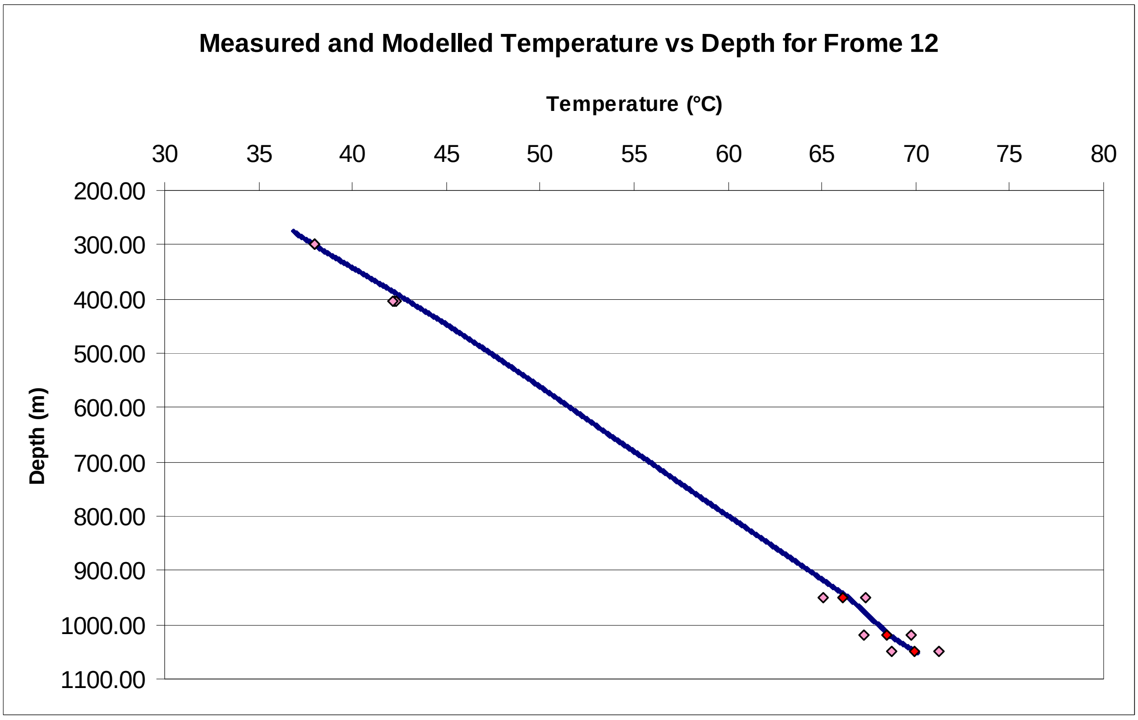


Figure 7b*. Measured temperatures (blue line) for borehole Frome 12. The modelled temperatures for the base of each thermal conductivity section (red diamonds) and the error bounds for each predicted temperature (pink diamonds) are shown.*

TM9W1

TM9W1 is located in the Lake Frome region, South Australia, approximately 175 km west-northwest of Broken Hill (Figure 1) and was drilled by Miner Administration. It was logged by GA several years after drilling.

Visual inspection of the measured temperature log shows that above 340 m true depth the gradient is disturbed. The heat flow determination is based only on data below this point.

The measured temperatures and depths at which core samples were taken are presented in Figure 8a. The assignment of thermal conductivities to depth intervals for TM9W1 was treated differently to other boreholes presented in this study. On inspection of the drilled core it was noted that from approximately 340-450 m depth, the lithology consisted of inter-bedded siltstone and limestone. One sample from each of these lithologies was collected and it was assumed that these two samples were representative of each limestone/siltstone layer throughout the ~110 m section. Due to the distinct difference in carbonaceous content between limestone and siltstone, the bounds of each inter bed were well defined in the natural gamma log. It was, therefore, possible to assign each interval an appropriate thermal conductivity value despite having collected only two samples between 340-450 m. Table 8a shows the sample name and depth interval(s) assigned to each sample. Table 8b shows the thermal conductivities measured for each sample and the depth at which each sample was taken.

The calculated heat flow for TM9W1 is 80 ± 3 mW/m^2. The measured and modelled temperature data versus depth are plotted in Figure 8b.

Table 8a. *Summary of sample information for TM9W1 including thermal conductivity and depth interval*

Sample Name	Lithology	Sample depth (m)	Number of Discs	Thermal Conductivity (W/mK)	Standard Deviation (W/mK)
Tele/1	siltstone	167	3	2.34	0.14
Tele/2	mudstone	266	2	3.33	0.03
Tele/3	limestone	366	2	2.44	0.05
Tele/4	siltstone	375	3	2.77	0.07
Tele/5	quartz vein	467	2	5.35	1.27
Tele/6	chert	542	2	3.79	0.19
Tele/7	siltstone	675	2	3.16	0.27
Tele/8	granite	762	2	2.90	0.01

Table 8b. *Sample name and depth interval(s) assigned to each sample for TM9W1*

Sample Name	Section Top (m)	Section Bottom (m)
Tele/4	345	360
Tele/3	360	373
Tele/4	373	382.0
Tele/3	382.0	392.0
Tele/4	392.0	411.0
Tele/3	411.0	425.0
Tele/4	425.0	455.0
Tele/5	455.0	490.0
Tele/6	490.0	575.0

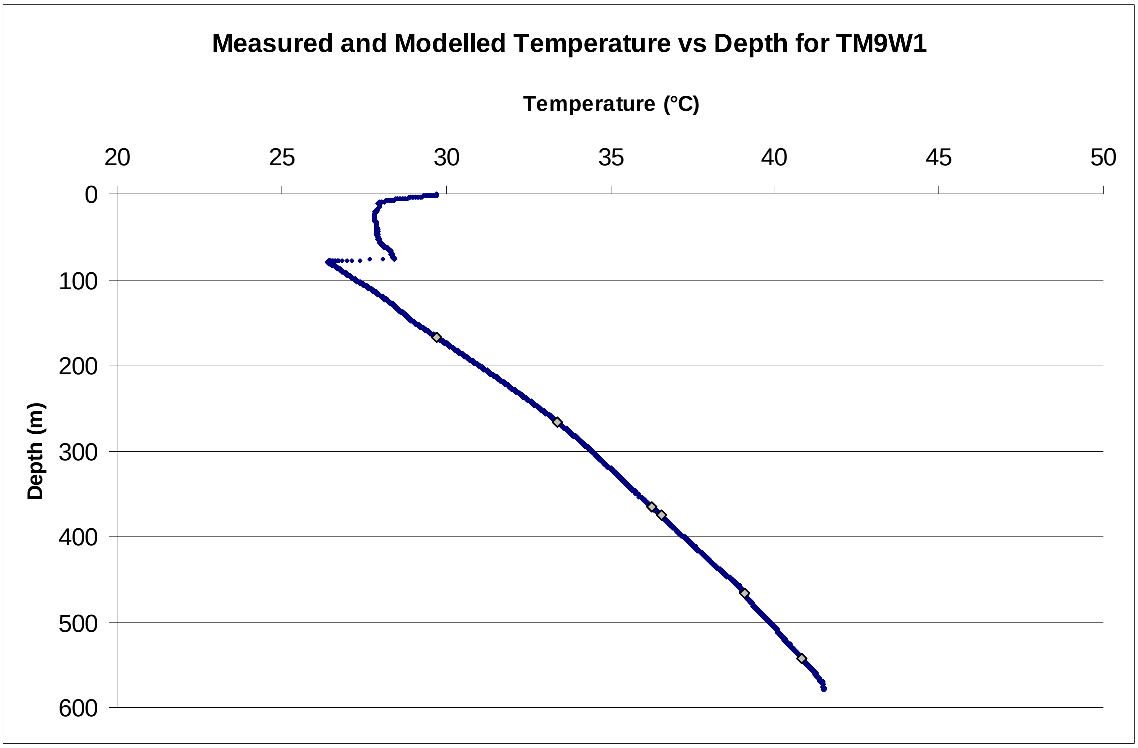


Figure 8a. *Measured temperatures (line) for borehole TM9W1. The depths at which thermal conductivities were measured are marked (diamonds).*

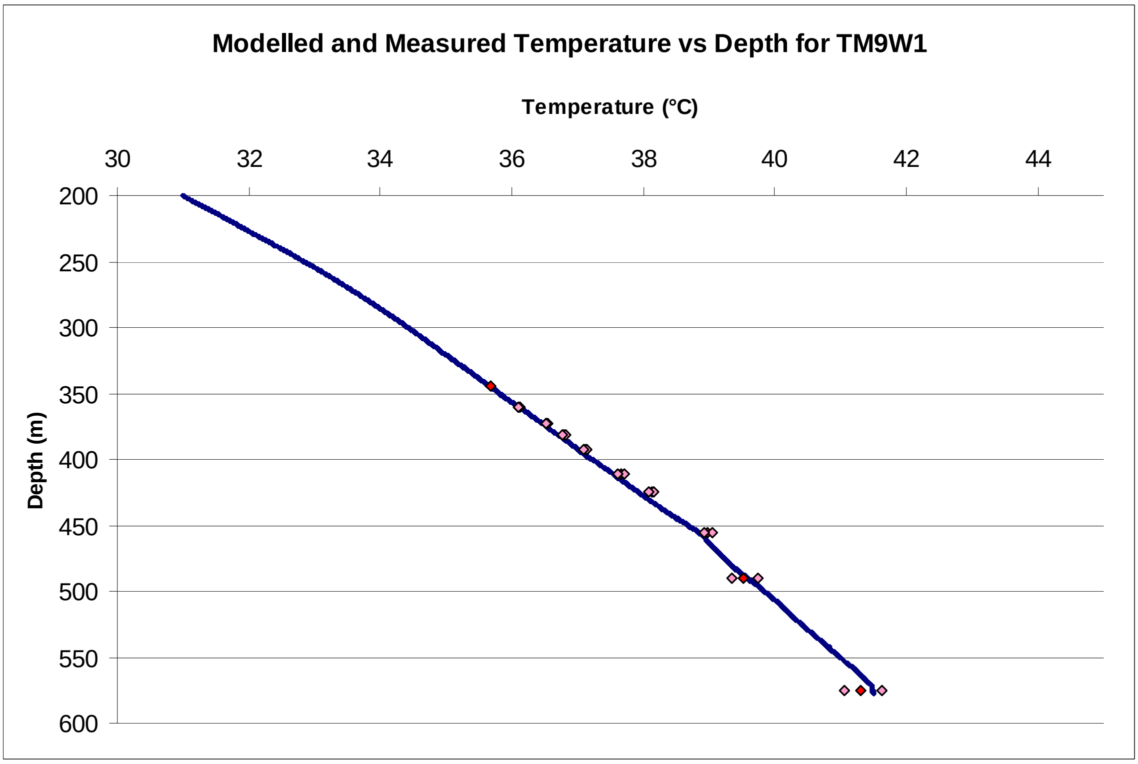


Figure 8b. *Measured temperatures (blue line) for borehole TM9W1. The modelled temperatures for the base of each thermal conductivity section (red diamonds) and the error bounds for each predicted temperature (pink diamonds) are shown.*

Discussion

New heat flow determinations have been presented here for two areas of Australia: the Eastern Goldfields region, WA, and Eastern South Australia. In the Eastern Goldfields region, three heat flow determinations have been presented, with values ranging from 23 – 36 mW/m^2. These values are consistent with the predominantly low heat flow values that have been previously reported in the Eastern Goldfields region (Sass et al., 1976; Cull, 1982). Three new heat flow determinations have also been presented from Eastern South Australia, ranging from 79-103 mW/m^2. These are consistent with reasonably high heat flow values that have previously been reported in this region (Jaeger, 1970; Sass et al, 1976; Lilley et al. 1977; Cull, 1982).

The temperature log for borehole PND0010 appears to be heavily affected by heat flow processes other than conduction. The large change in temperature at 300-350 m depth may indicate the flow of groundwater through the system. The upper 300 m of the profile also appears disturbed. Since the dominant thermal regime within this borehole does not appear to be well represented by 1D, steady state conduction, no heat flow value has been provided for PND0010.

As previously stated, heat flow is the product of thermal conductivity and temperature gradient. The first method outlined in this study generally attempts to find an average or single heat flow value for a specific drillhole. However, using this 'best fit' approach, the variation in heat flow with depth is masked. The second method, used for boreholes GWDD13 and TWDD0315, allows delineation of variation in heat flow with depth, with the standard deviation providing an indication of the magnitude of that variation.

An alternate method outlined by Lilley et al. (1977) may also be used when trying to delineate heat flow variation with depth. In this method, rather than calculating a single heat flow per borehole, a value for heat flow is determined at every interval for which thermal conductivity data is available. Each thermal conductivity value is assigned a depth interval. The temperature gradient over each interval is then determined from the measured temperature log. An interval heat flow is then calculated from the product of the thermal conductivity and temperature gradient. The final heat flow is the mean of the interval heat flows. The error on this value is taken to be the standard deviation of the interval heat flows. A potential source of error that can occur using this method is that, like the other methods used in this study, the reported heat flow value can become dependent on the interval selected to represent the thermal conductivity data. If the interval selected is too small, the result may be affected by noise in the temperature data. If the interval selected is too large, the thermal conductivity data may no longer be representative of the lithology of the interval.

Unfortunately, using a 1D approach to modelling heat flow causes horizontal heat flow to be ignored, a limitation that is always present regardless of the method used. The heat flow determinations calculated in this study, should be accepted with knowledge of the limitations and uncertainties of both the method used and the input data.

Conclusions

The heat flow values determined in this study are consistent with previously determined values for the surrounding regions. These new values improve the spatial distribution of public available heat flow determinations within Australia and will provide a better understanding of the thermal structure of the continent.

The interpretations contained in this report form the second release of heat flow data from Geoscience Australia's Geothermal Energy Project. The first release was released in October 2010 (Kirkby and Gerner, 2010); a third release is in preparation (Weber et al., in prep). The collection of new temperature and thermal conductivity data is ongoing, and so far temperature logs have been collected from 168 drillholes over all states and territories of Australia. Core samples have been collected from many of these holes, and further heat flow determinations will be released from these holes as thermal conductivity data become available.

References

Bullard, E. C., 1947. The Time Necessary for a Borehole to Attain Temperature Equilibrium. Geophysical Journal International, Vol. 5, p127–130.

Cull, J.P., 1982. An Appraisal of Australian Heat-Flow Data. BMR Journal of Australian Geology and Geophysics, No. 7, p11-21.

Cull, J. P. and Sparksman, G. F., 1977. Measurements of Surface Heat Flow. Geoscience Australia Record, 1977/39, 17pp.

Hales, A. L., 1937. Convection Currents in Geysers. Geophysical Journal International Vol. 4, p122–131.

Horton, C. W. and Rodgers, F. T., 1945. Convection Currents in a Porous Medium. Journal of Applied Physics, Vol. 16, p367-370.

Jaeger, J. C., 1970. Heat flow and Radioactivity in Australia. Earth and Planetary Science Letters, Vol. 8, p493-511.

Kirkby, A. L. and Gerner, E.J., 2010. Heat Flow Interpretations for the Australian Continent: Release 1. Geoscience Australia Record 2010/41, 28pp.

Lilley, F. E. M., Sloane M. N. and Sass, J. H., 1977. A Compilation of Australian Heat-Flow Mmeasurements. Journal of the Geological Society of Australia, Vol. 24, p439-455.

Sass, J.H., Jaeger, J.C. and Munroe, R.J., 1976. Heat Flow and Near Surface Radioactivity in the Australian Continental Crust. United States Geological Survey Open File Report, No. 76-250.

Weber, R.D., Kirkby, A.L., and Gerner, E.J., in prep. Heat flow determinations for the Australian continent: Release 3. Geoscience Australia Record.

Acknowledgements

We would like to thank Geothermal Resources Limited, Poseidon Nickel Limited, and St Barbara Limited for allowing us access to their drill holes and providing assistance with drillhole access and core sampling. We would also like to thank John Spring and field assistants for collecting temperature logs and core samples.