Heat flow modelling and thermal history of the onshore Gippsland Basin: upside potential for unconventional gas and geothermal resources

Ben Harrison[1], David Taylor[2], Peter Tingate[2], Mike Sandiford[1]

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Abstract

We present the results of heat flow analysis from downhole temperature logging and thermal conductivity measurements of boreholes in the onshore Gippsland Basin. Calculated borehole heat flow varies between 35–105 mW/m², with a mean of 68 mW/m².

Temperature builds relatively rapidly with depth, with gradients of about 35–80°C/km, because most of the stratigraphy provides good thermal insulation. Thermal conductivity measured on Cainozoic cores reveal lower than global average values, mainly due to high porosity, abundant coal, and low quartz content. Despite being more compacted, the Mesozoic Strzelecki Group is also relatively insulating due to muddy, quartz-poor lithologies.

Thick brown coal sequences in the Latrobe Valley area create temperatures of about 60–70°C at the base of the Cainozoic section to depths of 800 m, because of their high thermal resistance. This warmed water may prove commercial for low-enthalpy power generation, for input into current coal-fired plants, in direct-use applications, and highlights the possibility of stand-alone geothermal power generation from deeper, hotter sources.

A zone of anomalously low heat flow has been mapped in the east, mostly restricted to the Cainozoic strata. Comparison of bottom-hole temperatures predicted from heat flow modelling and gradient analyses with precision temperature log data suggest that temperature is locally being suppressed in the Cainozoic section by the removal of heat, probably by large volumes of groundwater flow (advection). Our temperature mapping delineates the distribution of this thermal disturbance and shows strong correlation to previously mapped regions of greatest groundwater flow. The Traralgon Formation coincides with this region of groundwater flow, where the sequence forms the basal Cainozoic unit above the tight groundwater basement of the Mesozoic Strzelecki Group. The thermal disturbance is largely absent in the Mesozoic strata.

The large volumes of groundwater flowing through the formation could potentially increase biogenic methane production for coal seam gas plays. The Strzelecki Group is also a potential source for tight gas and possibly shale gas. The present temperature regime, plus a much higher palaeo-temperature regime, shows that much has been into and may remain in the gas window.

1 School of Earth Sciences, University of Melbourne, Victoria, Australia. Email: harb@student.unimelb.edu.au.

2 Geological Survey of Victoria, Melbourne, Victoria, Australia

Introduction

The Gippsland Basin is a multi-commodity basin containing reserves of oil, gas, brown coal, heat, and groundwater, and with significant geological carbon storage potential. The demands for these resources are increasing, and more information is required to manage their development and exploitation in an environment of potentially competing interests. Integrated basin modelling depends on many parameters, including confident heat flow estimates of the past and present regimes. In turn, heat flow estimates are reliant on basic thermal and physical data: temperature and thermal conductivity, porosity, density, and groundwater movement. We present here the results of investigations and analyses of downhole temperature measurements and the thermal conductivity of samples from 34 boreholes in the onshore Gippsland Basin.

Past thermal regimes show that much of the onshore (gas-prone) Strzelecki Group has been in the hydrocarbon generation window. Vitrinite reflectance (VR) across the region is commonly about 0.5–0.7% near its top surface and reaches 1.2–1.7% at several kilometres depth (Mehin & Bock 1998; Figure 2). Several recent boreholes from across the region such as Megascolides-1 in the west and Wombat-4 in the east have intersected shows of tight gas. Overbank and lacustrine shales within the Strzelecki Group sequence may have potential for shale gas, similar to those being explored in the Nappamerri Trough, Cooper Basin (Trembath et al, 2012). The presence of a thermal anomaly associated with groundwater flow in major coal seams may also increase the likelihood of biogenic generation of coal seam gas.

Early exploration for conventional hydrocarbons in Gippsland mainly moved offshore in the 1970s, when the world-class Bass Strait fields were discovered. As these conventional fields are depleted and unconventional resources become more economically attractive, the relative ease of onshore exploration and the close proximity of the Gippsland region to major markets and existing infrastructure make the region worthy of further exploration.

Although a mature basin in exploration terms, dedicated data for heat flow studies (such as precision downhole temperature logging and thermal conductivity measurements) have only started to be collected in the last few years by the recent entry of geothermal explorers, researchers, and the Geological Survey of Victoria. Previous temperature studies mainly used bottom-hole temperatures (BHTs) from petroleum or water bores which lack the same level of detail and precision. This recent exploration and research effort thus provides greater insight into the subsurface temperature distribution, and the processes and mechanisms that control basin heat flow. The focus of this contribution is to present the new heat flow data and temperature modelling that highlights the distribution of a thermal anomaly of temperature suppression in the near-shore Cainozoic stratigraphy.

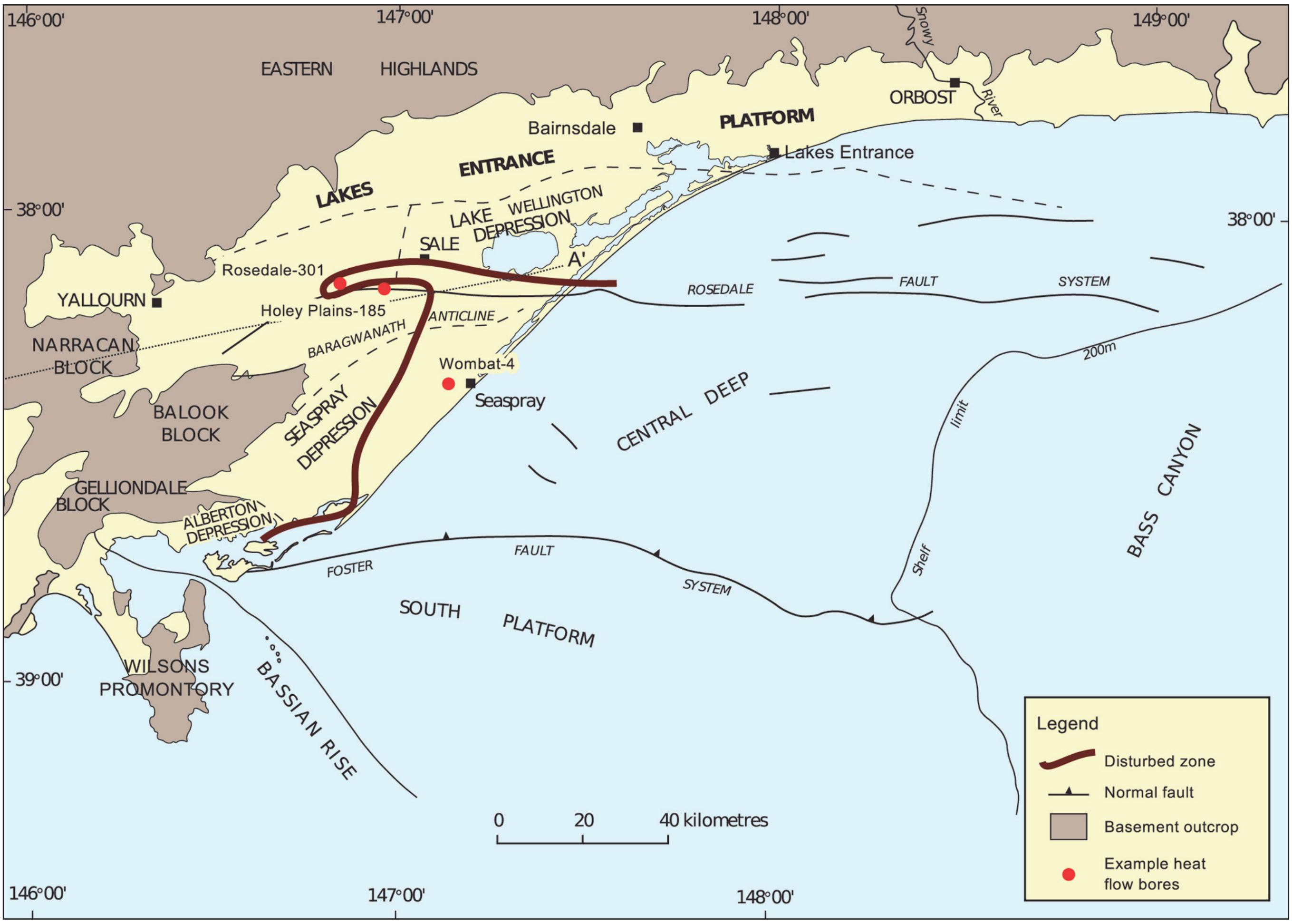

Figure 1. Map of the onshore Gippsland Basin showing: zone of thermal disturbance (yellow line); location of bores described in text with heat flow analysis (red circles).

Geological setting

The Gippsland Basin forms part of the southern break-up margin between Australia and Antarctica. The basin represents a symmetric, failed arm of the southern margin rifting, having become stranded and isolated when the east-west break-up of the Tasman Sea accelerated (e.g. Norvick & Smith 2001; Teasdale et al. 2003; Taylor & Moore 2010). Deep extensional faults segment the basin into platforms and then terraces with sedimentary thickness markedly increasing toward a large 'Central Deep' (e.g., Duddy 2003).

The Mesozoic Strzelecki Group rift sequence is a thick (>3000 m) syn-rift fluvial facies suggestive of river systems flowing axially along the rift valley (see Duddy 2003 and references therein, particularly Constantine 2001 for extensive descriptions of the sedimentology and stratigraphy). Extensive muddy sandstones many metres thick containing ripped-up debris–including entire trees–probably represent catastrophic flood events surging through the rift. Background sedimentation is represented by channel sandstones of thinner beds with ripples and cross-beds, interspersed with mudstone overbank, abandoned channel, and lacustrine facies. This whole sequence is rich in volcanic lithics, feldspars, and clay whilst being poor in quartz.

The progression from rift to sag within the Gippsland Basin allowed a thick transgressional Cainozoic sequence of lagoonal, beach and marine sand, mud and carbonate to be deposited over the earlier Cretaceous rift sequence. Inboard of the rising sea level, thick and extensive deposits of swampy brown coal accumulated to create world class resources (e.g. Holdgate et al. 2000, and see Figure 2).

The onshore Gippsland Basin can be divided into two very distinct zones (1) the 'Western Block' where the lower rift sequence of the Cretaceous Strzelecki Group is widely exposed due to multiple episodes of basin inversion along north-easterly trending faults hard-linked to the basement and (2) the 'Eastern Depression' where the Strzelecki Group is more simply distributed across the basement, with structure still dominated by the original east-west extensional faults of rifting (Figures 1 and 2). In the Eastern Depression zone the undulating Strzelecki Group surface dips oceanward and is progressively buried by up to 1000 m of younger Cainozoic fluvial to marine sequences. These zones have different prospectivity for gas and geothermal as discussed below in the prospectivity section.

Previous Work

Early temperature-based studies relied on occasional point temperature data collected as ancillary measurements made during groundwater and petroleum exploration (e.g. Cull and Conley 1983;

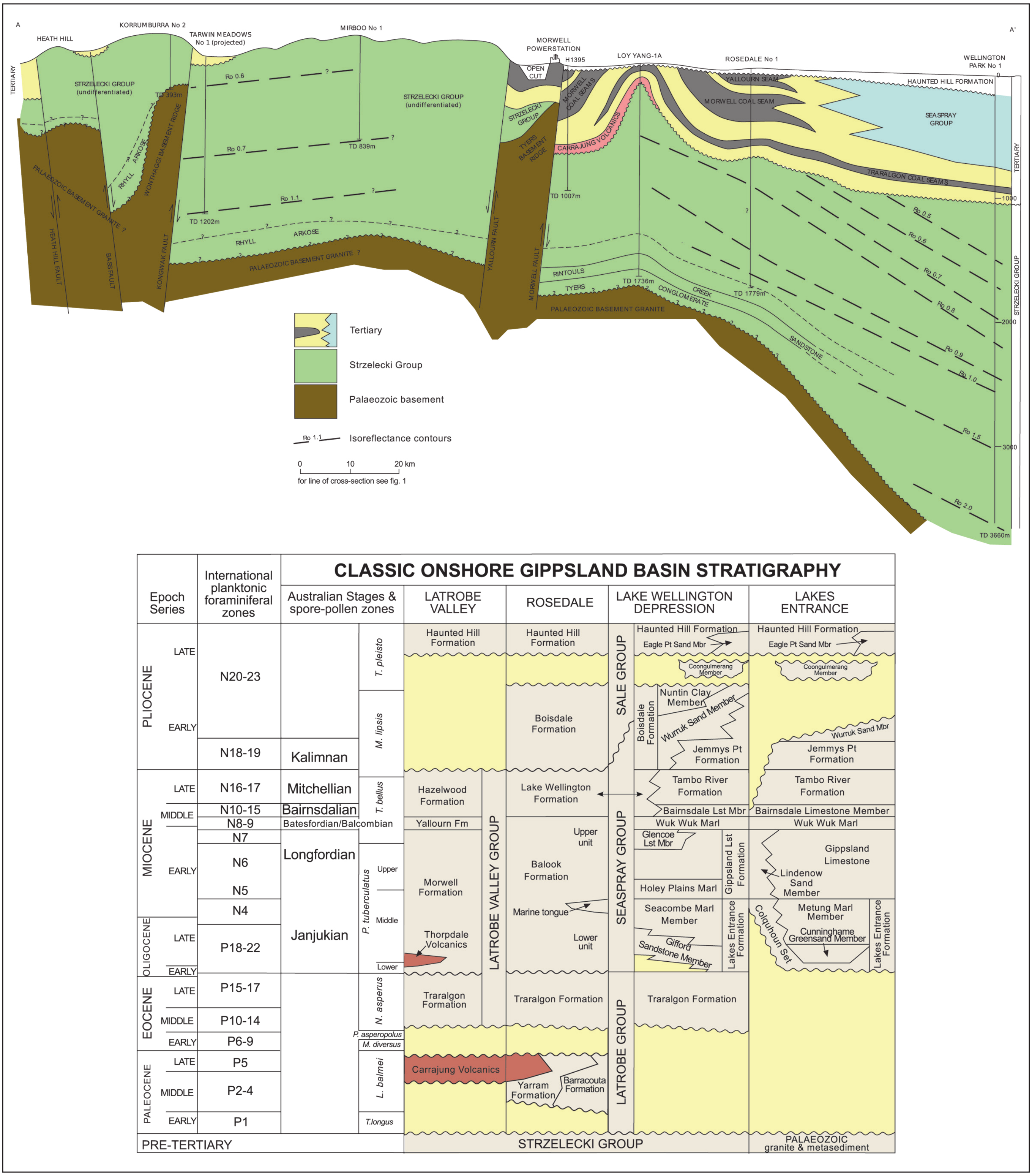

Figure 2. Regional cross-section (A-A' shown on Figure 1) showing vitrinite reflectance, and generalised stratigraphy for the onshore Gippsland Basin, modified from Holdgate & Gallagher 2003.

King et al., 1985; Featherstone 1991; Nahm 2002). A detailed catalogue of the BHT data from well completion reports and associated drilling has been compiled by the Geological Survey of Victoria (Driscoll 2006). The quality and treatment of this sort of well-log temperature data in particular have been discussed and assessed (Jessop 1990), highlighting the potential for considerable inaccuracy due to thermal disturbance from circulating drilling fluids, the low precision and thermal response time of industrial probes, and insufficiently detailed records of times. Indeed, several examples exist where new precision temperature logging has almost reached a BHT (usually boreholes now screened off at shallower depth) and found a very different temperature. For example, Sale-13 has a Horner-corrected BHT of 58.7°C at 1050 m but the precision log recorded a significantly higher temperature at a shallower depth with 67.2°C at only 950 m.

The first dedicated heat flow studies in the Gippsland Basin were also restricted to this point temperature data (e.g. Cull 1982; Cull & Beardsmore 1992), and had to assume thermal conductivities in the absence of direct measurements. Assumed conductivity values can be deduced from lithology and porosity estimates or by comparison to compilations of global averages, such as those summarised in for example Clauser & Huenges (1995) and Beardsmore & Cull (2001). Another approach, in the absence of direct conductivity measurements, is to deduce empirical estimates from geophysical well-logs (Goutorbe et al. 2008; Pechnig 2011). Few measurements of the thermal conductivity of Gippsland Basin sediments have previously been published (e.g. Cretaceous Strzelecki Group sandstone sample measured at 1.6–1.7 W/mK: Barker et al. 1998).

An estimate of the geothermal potential for the Australian continent was recently made (Hot Dry Rocks Pty Ltd 2011) using public domain data from the Global Heat Flow database (IHFC 2010), and company releases, and unpublished data from a number of sources, including some data from regions where the authors have conducted in-house research. The heat flow values are not listed individually however.

The Geological Survey has now compiled about 200 thermal conductivity measurements for the Gippsland Basin so that reasonable estimates for most formations and their constituent lithologies can be made. Some of these data were collected by the Geothermal Exploration Permit holders Granite Power Ltd, Greenearth Energy Ltd, and MNGI Pty Ltd. Greenearth Energy Ltd provided an Inferred Resource under the Geothermal Reporting Code covering 27.5 km^2 for their Wombat Geothermal Play near Seaspray (Greenearth Energy Ltd 2009), as well as a heat flow map within their Gippsland Basin permit areas. For simple temperature-at-depth analyses, thermal conductivity profiles may be avoided altogether by instead performing calculations purely from geothermal gradients (e.g. Somerville et al. 1994). This approach has also been undertaken in this study, in many wells inaccessible for precision logging, to help broaden the study's coverage and complement the borehole heat flow modelling. Newly-gathered downhole precision temperature log data and thermal conductivity measurements have allowed detailed heat flow modelling and temperature gradient analyses, and provide the necessary constraints for future detailed thermal modelling.

Methods

Surface heat flow determination

The precise determination of heat flow in boreholes requires coincident temperature gradient and thermal conductivity measurements. For meaningful analysis of thermal gradients, precision borehole temperature logs are best obtained from cased boreholes at a sufficient time after the cessation of drilling activity such that the thermal disturbance caused by circulating drilling fluids has dissipated. Thermal conductivity measurements are best made on intact core from intervals with a uniform lithology. In combination, an interval of unchanging or 'steady' temperature gradient within a uniform lithology gives the greatest confidence in heat flow calculations, with the lowest possible uncertainty. The Geothermal Exploration Permit holders (Greenearth Energy Ltd, Granite Power Pty Ltd, and MNGI Pty Ltd), the Geological Survey of Victoria, and the research community (University of Melbourne, Monash University, Hot Dry Rocks Pty Ltd) have collected precision temperature logs from about 50 boreholes, mostly water bores that remain accessible as part of the State Observation Bore Network (SOBN). About half the logs could only access shallow depths (less than 200 m logged) and some logs did not provide sufficiently stable temperature intervals for heat flow modelling. To better constrain heat flow modelling from this temperature data, around 200 new thermal conductivity measurements were also taken for stratigraphic units intersected in the bores.

Borehole temperatures and thermal gradients

Bottom-hole temperatures (BHT) are routinely measured during exploration drilling for hydrocarbons, typically using a maximum temperature instrument. The maximum temperature thus recorded reflects the fluid temperature at the time of drilling, which is not an accurate record of virgin rock temperature. With prudence some BHT data may be used to generate geothermal gradients over the length of a well, to provide first-order constraints for thermal modelling.

Despite the large uncertainties inherent in temperature data from hydrocarbon wells, they are the only source of information in offshore areas, as well as many onshore areas. In the onshore Gippsland Basin a broad network of boreholes have been acquired for inclusion in the SOBN as part of the legacy of decades of brown coal and petroleum exploration and heavy groundwater utilisation by industry and the agricultural sector. Many of these bores were drilled and logged for stratigraphic investigations by the State Electricity Commission of Victoria (SECV) and the Geological Survey of Victoria, and have preserved drill core and additional data such as geophysical well-logs.

Downhole temperatures were uniformly logged using thermistor-type probes at depth intervals ranging from 1–5 m depending on stratigraphy, depth, and time constraints, though mostly spaced at 1 m, with depths reported from the natural ground surface. Several probes of similar manufacture were used over the course of the research effort (each with a precision of ±0.0001°C, and absolute accuracy ±0.01°C) attached to a ~800–1000 m kevlar-reinforced cable with a mechanical depth counter. From these measurements thermal gradients were generally calculated throughout the length of the temperature log over consecutive readings – intervals of 2–4 m depending on the initial resolution of the temperature log – and plotted to aid visual inspection. Inspection of the gradient plots allowed selection of intervals with unperturbed and steady (i.e. unchanging) gradient profiles for heat flow analysis. The mean gradient of an individual steady interval is determined by a simple average, or by linear regression, with confidence level determined by the standard error of variations of individual values from the mean.

Thermal conductivity

Thermal conductivity measurements are scarce. Numerous indirect methods have been proposed for estimating thermal conductivity – such as that demonstrated by Goutorbe et al. (2006), and the many references therein – however resulting estimates may be imprecise due to multiple factors beyond the control of the experimenter. Some of these methods require a training set of measured thermal conductivities to provide a baseline from which to establish empirical relationships between geophysical well log data and thermal conductivity (e.g. Griffiths et al. 1992; Hartmann et al. 2005). Implicit in these methods is the site-specific nature of the relationships, due to the specific nature of the mineralogy, textures, fabrics, porosity, and other characteristics of the sedimentary rocks in that area. In the present study, the availability of preserved core, a state-of-the-art thermal conductivity laboratory, and the support of the Geological Survey of Victoria allowed us the opportunity and resources to determine direct measurements of thermal conductivity for the bulk of the rocks in the Gippsland Basin with nearly 200 samples now measured.

Drill cores were sampled to retrieve about 10 cm of competent core (the specimen), which was then cut to three cylindrical samples of 2–3 cm length. Some samples were too friable to be prepared in this manner, and were instead placed into a specially-prepared ‘hollow cell’ (see Sass et al. 1971 for further discussion of the procedures and precision of this method). Thermal conductivity was measured on intact lengths of core where possible in a divided bar apparatus following saturation in water under a vacuum. All measurements were made under consistent conditions at the laboratory of Hot Dry Rocks Pty Ltd, Melbourne, and the harmonic mean of the triplicate samples returned as the sample thermal conductivity value.

Some discussion of the sampling is warranted as it likely has impacts on the outcomes of the subsequent statistical treatment of the analyses. Most of the bores with retained drill core in the onshore Gippsland Basin were completed during a series of drilling campaigns through the 1980s, with emphasis on sampling of the Cainozoic basin-fill. The preservation of the Cainozoic drill core varies considerably, so efforts were made to ensure samples were selected equally from all lithologies. However some bias towards the better preserved rocks is to be expected. In some cases anomalously high conductivity on occasional samples could be correlated to outliers in wireline logs, such as density, and this presumably reflects small atypical horizons (and cores) affected by secondary cementation. As all of the bores sampled were drilled vertically, and heat flow is dominantly in the same orientation, that is, axial to the core, no special examination of the anisotropy of the rocks was made, and it is assumed that the broad sampling of bores across the basin encompasses variations in bedding angle and other planar features of the subsurface that contribute to variations in the thermal conductivity tensor.

Heat flow modelling

Interval analysis method

Interval analysis uses intervals where there are adjacent temperature and thermal conductivity data. The method is useful in situations where a high degree of precision is required for

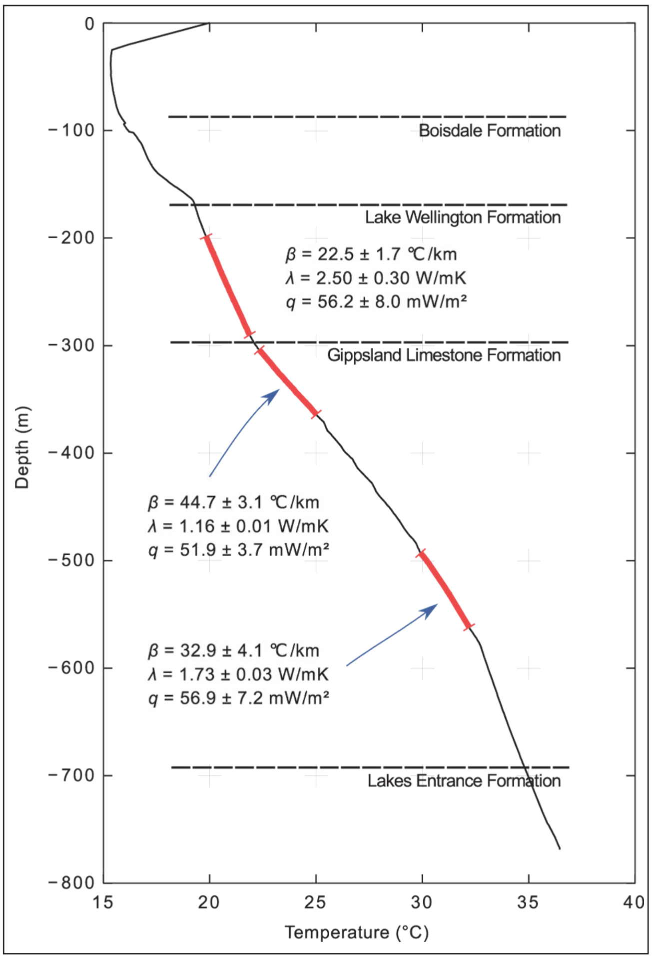

Figure 3a. Interval heat flow analysis for Holey Plains-185 [average of three intervals: 55.0±3.6 mW/m²].

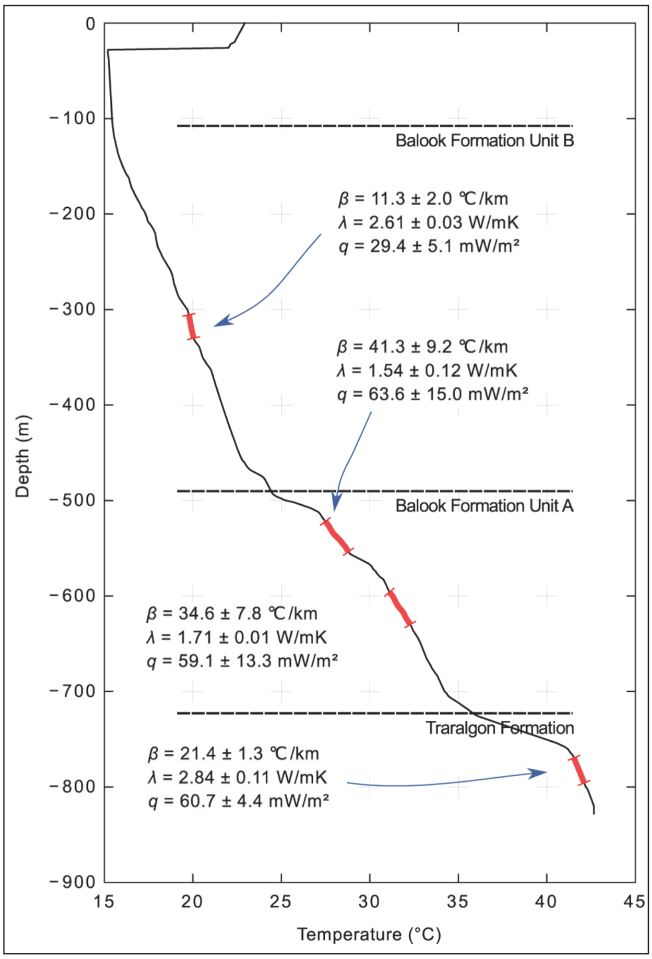

Figure 3b. Interval heat flow analysis for Rosedale-301 [average of lower three intervals: 61.1±6.3 mW/m²]. The uppermost interval has a very poor agreement of lithology and gradient (possibly due to hydrological affects), and was discarded from the final borehole heat flow calculation.

discrete borehole depths, so long as there are sufficient data. In the absence of physical measurements of thermal conductivity in the borehole being studied (i.e. only estimates of thermal conductivity are available), whole-bore heat flow modelling is a more appropriate approach. In this study, the interval analysis method is demonstrated for two boreholes in depth intervals where drill core has been sampled and measured for thermal conductivity (Figures 3a and 3b).

The vertical heat flow density q (W/m²) may be calculated from borehole data using the expression:

$q = \lambda \cdot \beta$ … (1)

The solution to Eqn. 1 requires measurements or confident estimates of the thermal conductivity λ (W/m/K) and the temperature gradient β (K/m). The required assumptions of purely conductive, purely vertical heat flow, in a steady-state equilibrium situation, with no internal heat production are made for convenience, though they are probably only truly accurate in rare situations. No data exist of heat production rates of the onshore Gippsland Basin Cainozoic sedimentary sequences, however they are likely to have a negligible effect considering their thickness and composition. Nor are there such data for the underlying Strzelecki Group. For their Inferred Resource calculations, Greenearth Energy Ltd 2009 applied an estimate of 1 µW/m³ within the Strzelecki Group, based on published data for similar rocks, which adds an additional 1 mW/m² for every kilometre thickness modelled. For our shallow borehole models we have ignored this contribution.

Thermal conductivity is a physical property of a substance or material. For mixtures like sedimentary rocks, thermal conductivity is dependent on a number of conditions, including temperature (Woodside & Messmer 1961, Brigaud & Vasseur 1989, Luo et al 1994, Chen 2008). Our measurements are reported for laboratory temperatures of nominally 25°C, and have not been corrected in the heat flow calculations below as most intervals are lower than 60°C, for which corrected conductivity values lie within the range of precision of the instruments.

Whilst the simple mathematics of heat flow analysis using Eqn. 1 can generate a quantitative number with some uncertainty, there are also some subjective parameters which affect how the resulting numbers should be viewed in qualitative terms. Data quality, availability, and variability requires us to assign confidence ratings to the resulting *borehole heat flow estimations*, simplified here:

GOOD – Borehole shows a good correlation of lithology variations to temperature gradient variation, and several interval analyses give concordant heat flow estimates with overlapping uncertainties;

MODERATE – Borehole shows fair correlation between lithologies and gradient and yields several concordant heat flow estimates that may involve using conductivity estimates from nearby bores (i.e. we accept these estimate with some reservation);

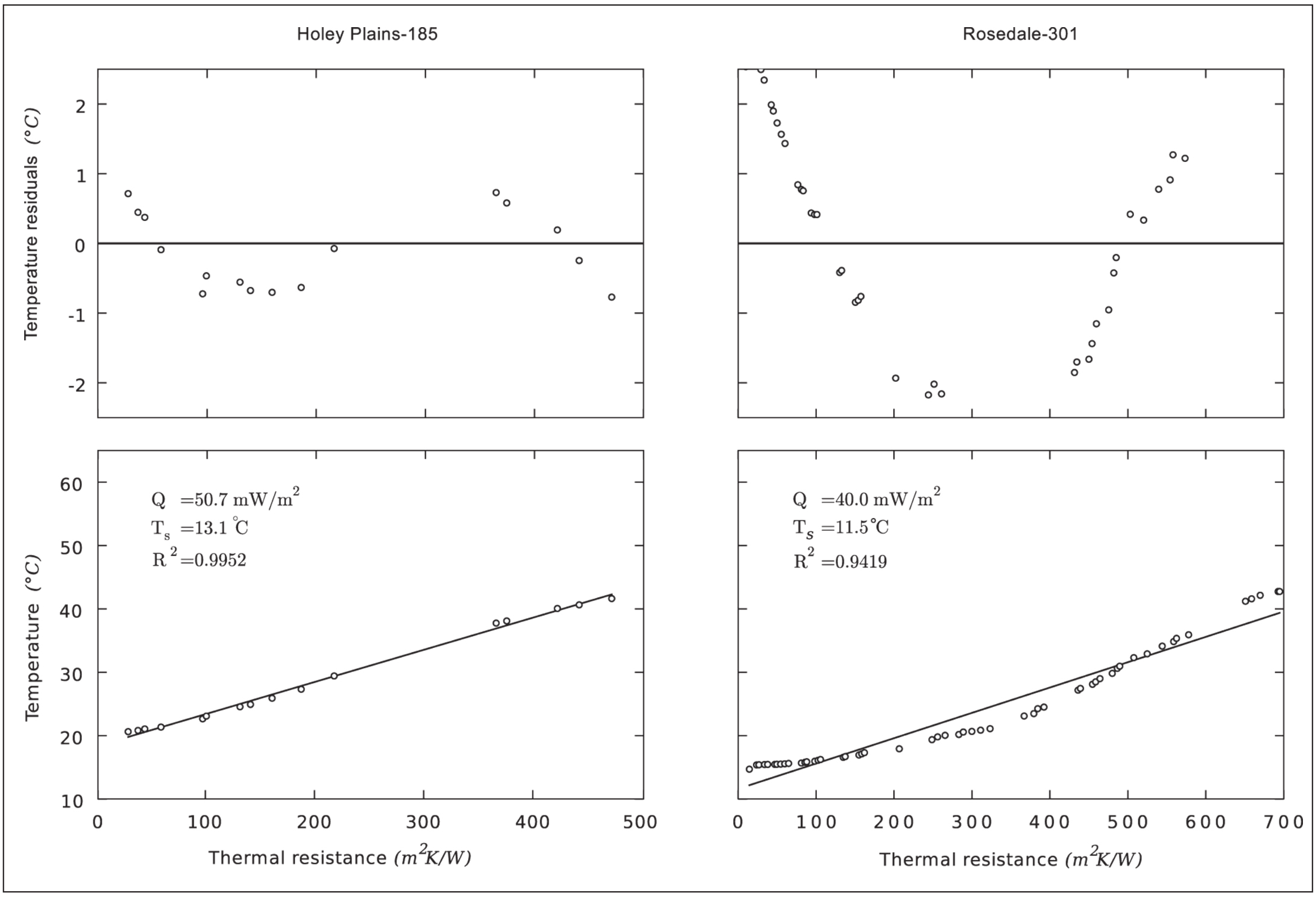

Figure 4. Example Bullard Plots and temperature residuals for Holey Plains-185 and Rosedale-301. Results of linear regression are inset in the Bullard Plots, where the coefficient of determination R^2 is a measure of the fit of the regression line to the data. Colours are for visual differentiation of curves only.

POOR – Borehole starts to show breakdown of correlation between lithology and gradient to suggest steady state conditions are being affected by hydrological disturbance, palaeoclimate signals, etc. Often only one or two concordant heat flow estimates were obtained with outliers sometimes having to be discounted (i.e. treat with caution);

UNRELIABLE – Borehole with large discordance between lithology and gradient with a lack of stable intervals of temperature gradient preventing measured or assumed conductivity from being applied to create a heat flow estimate. Unreliable holes can also have results from several discordant heat flow estimates with no obvious indication as to which should be preferred (i.e. results from these bores are just as likely to misinform instead of adding scientific value).

Two examples of the interval method calculations performed are given in Figure 3a (Holey Plains-185) and Figure 3b (Rosedale-301). In the former, the borehole heat flow estimate is rated as 'moderate', due to a slight mismatch in gradient and lithology. In the latter example, three intervals are at depths greater than 500 m and in close agreement with each other. The uppermost interval has a poor agreement of lithology with gradient, and was discarded, leading to a borehole heat flow estimate rating of 'poor'.

Thermal resistance method

Thermal resistance is the measure by which a body resists heat flow in the presence of a temperature difference, and is the

Borehole	Bore ID	Latitude	Longitude	T-log depth (m)	Heat flow (mW/m^2)	Heat flow rating
Bairnsdale-15005	47063	-37.903	147.625	564	87±5	Good
Bore 147174	Private	-38.636	146.749	158	99±11	Moderate
Bundalaguah-8	52742	-37.973	147.000	138	76±18	Poor
Corinella-139	56922	-38.417	145.524	78	79±8	Poor
Denison-50	440058	-38.112	146.893	380	58±7	Poor
Denison-53	58935	-38.107	146.897	287	70±10	Poor
Denison-57	58937	-38.069	146.855	719	84±16	Poor
Drouin East-1	61125	-38.185	145.889	60	67±11	Poor
Holey Plains-185	67441	-38.167	146.956	768	55±4	Moderate
Koo-Wee-Rup-12	71187	-38.168	145.515	78	58±8	Poor
Koo-Wee-Rup-18	71192	-38.212	145.466	85	35±5	Poor
Koo-Wee-Rup East-4	71846	-38.176	145.704	156	105±21	Poor
Koo-Wee-Rup East-9	71851	-38.143	145.608	118	81±17	Poor
Koorooman-15001	71148	-38.480	145.970	69	57±7	Poor
Lang Lang-193	74309	-38.316	145.517	115	75±14	Poor
Leongatha-24	75404	-38.505	145.850	68	56±7	Poor
Loy Yang-1675	374749	-38.179	146.632	618	53±6	Moderate
Loy Yang-20002	353595	-38.252	146.560	713	79±7	Moderate
Loy Yang-2390	374946	-38.176	146.647	683	72±7	Moderate
Maryvale-2390	77436	-38.205	146.454	142	67±6	Poor
Meerlieu-15001	77945	-38.006	147.285	700	57±4	Moderate
Rosedale-301	89809	-38.155	146.838	828	61±6	Poor
Sale-13	90138	-38.115	147.218	950	75±3	Good
Tinamba-15083	95482	-37.993	146.907	72	53±7	Poor
Toongabbie South-36	376243	-38.135	146.677	609	56±7	Poor
Toongabbie South-37	376244	-38.154	146.517	304	78±20	Poor
Traralgon-286	96560	-38.189	146.541	542	73±7	Moderate
Winnindoo-46	103583	-38.106	146.730	652	65±16	Poor
Wombat-4	965482	-38.369	147.128	1770	62±10	Poor
Woranga-12	110726	-38.564	146.748	527	73±8	Moderate
Wurruk Wurruk-13	105548	-38.116	147.019	168	80±12	Poor
Yallock-11	106103	-38.178	145.569	105	60±13	Poor
Yallock-9	109784	-38.216	145.612	125	52±8	Poor
Yannathan-1	109787	-38.237	145.659	85	56±8	Poor

Table 1. Boreholes with heat flow determined from measured thermal conductivity and precision temperature log data using the interval analysis method, onshore Gippsland Basin. Bore ID refers to Geological Survey of Victoria's identifier.

integrated inverse of thermal conductivity. That is, an individual unit of thickness z has thermal resistance $R_T = z/\lambda$ (m²K)/W, and the thermal resistance of a series of units in a borehole is the sum of the individual unit thermal resistances. If we replace λ in (1) with z/R_T and $(T - T_0)$ for β and rearrange for the upper temperature T_0 we have:

$$T = q \cdot R_T + T_0 \ldots (2),$$

which is of the familiar linear form y = mx + b, where temperature is the dependent variable. A plot of measured downhole temperatures T against the cumulative thermal resistances R_T at the same depths (a Bullard Plot; Gallagher 1990) leads to a straight line where the slope is the vertical heat flow q, and the intercept T_0 is the ground surface temperature. Points on a Bullard Plot (see examples given in Figure 4) lie along the linear regression if the conditions are conductive, steady-state, and with no internal heat production, and the residuals should be randomly distributed about the zero residual line. The example shown for Rosedale-301 is an extreme example of non-linearity; most likely due to strong fluid migration removing heat from the uppermost ~500 m.

Results and Discussion

Available data

This paper focuses on new precision temperature data and heat flow modelling from the 34 boreholes in the onshore Gippsland Basin where the deepest holes and only reliable heat flow estimates are available. All of the raw precision temperature log data and thermal conductivity measurements from the combined research and exploration effort (more than 60 bores in total) are currently held by the Geological Survey of Victoria and are available on request, with a long-term view for the data to be bundled into a package that will become available online.

Borehole temperature data

Thirty-four of the precision temperature logs collected were used for heat flow analysis (see summary in Table 1; combined temperature-depth plots in Figure 5). Cumulatively these temperature log data aggregate to about 15 km of linear depth,

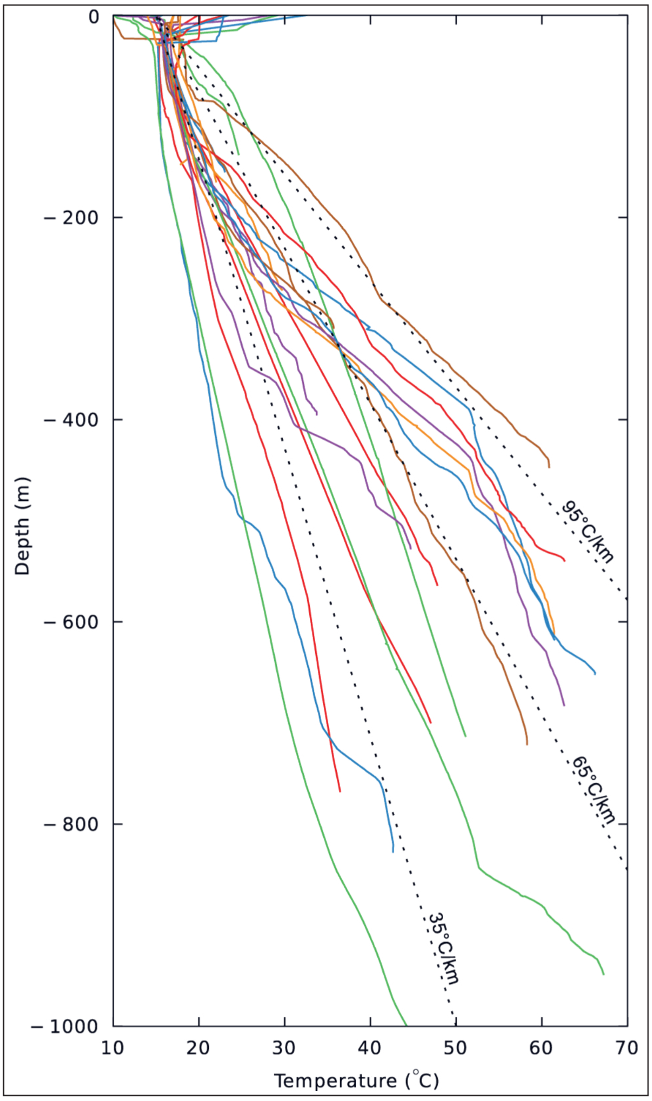

Figure 5. Precision temperature logs for 22 boreholes in the eastern onshore Gippsland Basin. Linear thermal gradients from a ground surface temperature of 15°C are shown for 35, 65, and 95°C/km as reference.

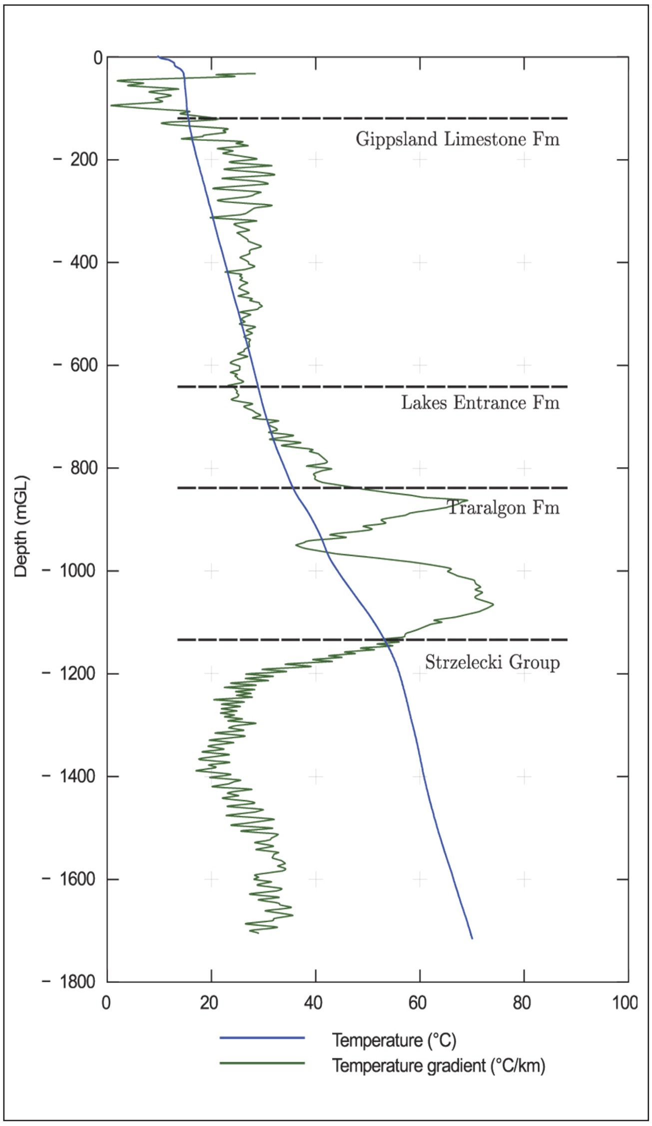

Figure 6. Precision temperature log and temperature gradient curve for onshore well Wombat-4.

with most bores sampled at 1 m intervals. The greatest depth and temperature were reached in Wombat-4, where 70.0°C was reached at 1714 m depth (Figure 6). The highest average gradient (calculated from surface to total depth of log) was ~104°C/km in Maryvale-942, where temperatures reached 60.8°C at 441 m depth. The ground surface temperatures interpolated from the precision logging average a little over 15°C which is two to three degrees warmer than the average annual air temperature obtained from climate data provided by the Bureau of Meteorology (<http://www.bom.gov.au/>) of ~13°C. This confirms the heuristic of Howard & Sass (1964) that mean ground surface temperatures typically differ by an average of 3.0°C from mean air surface temperature.

Abrupt changes in the downhole temperature gradient highlight large differences in conductivity between some of the units. This is particularly the case in the onshore sequences, where thin metre-scale fluvial sequences of interbedded sand, mud, and coal cause the geothermal gradient to appear as an apparently unstable and rapidly alternating log in response to the rapidly changing conductivity. This metre-scale distribution prevents long (>10 m) intervals of stable geothermal gradient from being established and thus hampers attempts to derive heat flow estimates from the traditional interval analysis approach (and lowers the confidence in any estimates made using this method).

The ideal conditions for interval heat flow analysis occur where several well-spaced intervals in a bore each have a uniform lithology, steady (i.e. unchanging) thermal gradient and well-constrained thermal conductivity measurements. Longer intervals with an unchanging gradient provide us with greater confidence in our analysis by supporting the assumption of steady-state conductive conditions. Non-linearity in a temperature-depth curve without changes in thermal conductivity is a sign of heat loss or gain to the vertical heat flux. In the Gippsland Basin pronounced non-linearity in the temperature-depth curve is primarily due to conductivity changes rather than a breakdown of the conductive heat flow assumption. To overcome this problem, bulk conductivity aggregation and Bullard Plot methods were employed to support heat flow estimates in such areas.

Thermal conductivity data

Nearly 200 thermal conductivity measurements from borehole cores from across the Gippsland Basin have now been collected, representing most of the formations present in the Gippsland Basin. Importantly, almost all of this work was undertaken through the laboratory of Hot Dry Rocks Pty Ltd, Melbourne using the same instruments (divided bar apparatus), operators, and conditions such that the results can be treated as a coherent data set. All the data has been compiled by the Geological Survey of Victoria and is available upon request, with an intention to publish the data once some final sampling is completed.

Regional thermal conductivity statistics were generated for lithological classes representative of all the stratigraphic units of the basin (Table 2). We report mean value with standard error (SE) of the mean, which may be used to estimate the upper and lower 95% confidence limits for sample means by the expression: Limit = mean ± (SE x 1.96), under the fair assumption that the distribution of our sample values is approximately Gaussian. Figure 7 shows stacked kernel density estimation plots for the lithological classes, which give a visual appreciation for the probability density function for each.

The classes for Cainozoic sequences are: sands, coal, clays, limestone, marls, quartz-rich marls, and dolomite. For the Mesozoic Strzelecki Group sequence the classes are: sandstone, mudstone, and siltstone. Values for the Cainozoic lithologies are somewhat lower on average than equivalent values from published compilations such as that in Beardsmore & Cull (2001, table 4.2) mainly because these Gippsland Basin rocks have high porosities, typically between 25–45%. Sampling bias towards consolidated

Lithology	n	λ (W/mK)	SE (W/mK)
(a) Cainozoic			
Clay	20	1.75	0.07
Coal	21	0.60	0.07
Dolomite	2	4.3	0.10
Limestone	20	1.79	0.08
Marl	13	1.38	0.08
Sand	17	2.32	0.13
Tambo River Fm	4	2.12	0.11
(b) Mesozoic			
Claystone	12	2.06	0.13
Sandstone	24	2.17	0.08
Siltstone	4	2.09	0.07
All Mesozoic	40	2.13	0.06

Table 2. Thermal conductivity means (λ) and standard error (SE) of the means for lithology classes for (a) Cainozoic samples, and (b) Mesozoic Strzelecki Group samples.

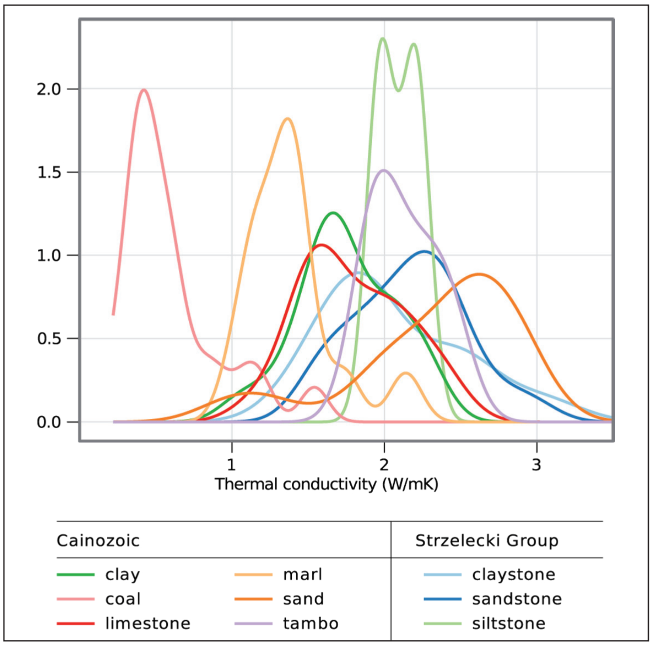

Figure 7. Kernel density estimate plots for thermal conductivity measurements of the main lithological classes, showing the statistical estimation of each class's probability density function. The kernel density estimate is a means of gauging the probability distribution of a population from a finite sample.

and competent pieces of drill core is noted and expected, due partly to the objectives of the drilling campaigns, and partly due to the age of much of the core held in the core library.

For lithologies that can be considered a combination of these primary lithologies, a series mixing law should be applied, appropriate to the mixing model of the lithologies, or the geometry of the strata. Beardsmore & Cull (2001) show that for interbedded units the harmonic mean applies, and for mixtures of lithologies either the geometric or square root mean applies. An example from the Latrobe Valley area is the ubiquitous 'ligneous clay' described in bore completion reports (e.g. Thompson 1980): from visual inspection of a number of examples, we determined a proportional composition to be approximately 80% clay, 20% coal, giving a weighted harmonic mean of thermal conductivity values of 1.27 W/mK.

Three of the major formations in the Gippsland Basin are dominated by brown coal deposits, with widely varying thicknesses: from centimetre-scale to continuous seams up to 165 m, each with multiple sequences of clay and sand (e.g., the Morwell seams of the Morwell Formation: Barton et al. 1993). The large contrasts between low-conductivity coal and relatively high-conductivity sands and clays is a problem for characterisation of bulk thermal conductivity for these formations. With such large differences in conductivity (sand 2.3 W/mK to coal 0.6 W/mK), even small differences in proportional abundances in the composition of these formations may lead to erroneous thermal conductivity estimates.

The borehole heat flow calculations presented below used these thermal conductivity values in preferential order: (a) samples measured within the borehole and interval of interest; (b) samples measured from adjacent boreholes of matching stratigraphy and lithology; (c) the statistical mean of the relevant lithology from all samples of a particular lithology (i.e. the values in Table 2).

Heat flow determinations from borehole data

Borehole heat flow calculated for 34 bores is presented in Table 1. The values span the range 35–105 mW/m², with a mean of 68 mW/m². This new mean heat flow from our regional data is consistent with some of the recently reported heat flow estimates undertaken by the geothermal explorers over individual resources (e.g. Greenearth Energy Ltd 2009). This regional estimate is also similar to earlier regional Gippsland Basin thermal models estimates of 60–80 mW/m² (Featherstone et al. 1991, Alexander et al. 1991).

Some early studies in the offshore using only assumed conductivities suggested higher heat flows but re-modelling with better informed conductivity values produces heat flows more in line with the new regional average. In the near-shore Barracouta-1 well Cull & Beardsmore (1992) used assumed conductivities and interpolated downhole temperatures from poorly-documented BHTs and formation tests, to produce four interval heat flow calculations ranging from 70–108 mW/m². Their heat flow estimate for the bore was in the range 90–110 mW/m², presumably after consideration of the quality of the individual interval analyses. Given its proximity to the coast, the substitution of measured onshore thermal conductivity values for the same four intervals gives three consistent heat flow estimates averaging ~70 mW/m² (the upper three intervals). The lowest interval returned a much lower value: ~35 mW/m², which may be ascribed to poor temperature records, or an atypical Upper Cretaceous lithology as mentioned in the well completion report, or perhaps hydrological disturbance.

Gallagher (1990) reports calculations from Volador-1 further offshore using two methods, both essentially combining corrected BHTs and poorly constrained thermal conductivities, to arrive at an estimate for surface heat flow of ~110 mW/m². However the author notes inconsistencies in the data leading to low confidence for this estimate.

Bullard Plots are a useful graphical tool to investigate conductive heat flow in a borehole, and were employed to assist with the interval heat flow analysis. Models of the thermal resistance were generated by assigning either primary values of thermal conductivity or by use of an appropriate mixing law to lithological logs for boreholes with temperature logs. Resistance values were then calculated for the base depths of each lithological unit, and plotted against the interpolated temperature at the same depth. Despite the high resolution of the temperature logs, their point depths do not coincide with the resistance depths, so a cubic-spline representation of the temperature data was used to interpolate values at exactly matching resistance data depths. Initial visual inspection of the plotted points allowed obvious outliers to be filtered (for most boreholes this was typically the near-surface; approximately 100–150 m, due to diurnal and seasonal surface temperature fluctuations), and a simple linear regression was performed over the remaining data.

Non-linearity of the plotted points to the regression line seen for example in Rosedale-301 (Figure 3b) highlight the deviation from our assumed conditions of a purely conductive, steady-state environment. Furthermore, a sense of the accuracy of the Bullard Plot method may be gained from the regression coefficient of determination (R^2), and the intercept value of ground surface temperature (T_s). To continue with the Rosedale-301 example, the R^2 of 0.9419 is low for this type of analysis, meaning that the regression line fits poorly with the data, and the T_s of 11.5°C is nearly 3°C less than climate data and temperature log data for the region tells us. So the bore is displaying a marked removal of heat, and further investigation is required to determine the causes and controls of heat flow.

Temperature-at-depth modelled from geothermal gradient analysis

In addition to modelling heat flow, a regional appreciation of the basin-wide thermal structure was developed by compiling predictions of temperature at depth from averaged geothermal gradients, aggregated for the specific stratigraphy of each well (see examples in Table 3 – full details intended to be published in a future paper). Since most of the stratigraphic packages were precision-logged multiple times in different bores across the basin, a regional average gradient for each stratigraphy was able to be derived. These averages were then applied to the individual stratigraphic units intersected in every deep borehole in the basin (33 deep groundwater bores and 38 deep onshore petroleum bores).

The spread of the measured bores (and their stratigraphies) from across the onshore basin and the relatively clustered distribution of heat flow around its mean value, suggests this averaging technique should still provide an adequate tool useful for regional analysis. Spatial averaging of thermal gradients for any particular unit within a sedimentary basin, measured in different areas of the basin each potentially subject to localised variations in heat flow (e.g. via advection), also provides a strategy to overcome localised departures from steady-state conditions that may exist unnoticed in heat flow modelling of individual boreholes.

Like many rift basins, geothermal gradients in the Gippsland Basin are higher than typical continental geothermal gradients of about 25°C/km. Gippsland Basin Cainozoic sediments are quite insulating (gradients of 35–80°C/km) due to low quartz content, high porosity and a high proportion of coal. Despite being more compacted, the underlying Strzelecki Group sequences also remain insulating (30–40°C/km) due largely to a predominance of muddy, quartz-poor lithologies.

In the western parts of the study area, the prediction of temperatures at depth closely matches historic observations where available (see Holey Plains-192 example in Table 3). Toward the coast in the east, where groundwater flow is concentrated into the more porous Cainozoic units, the predicted temperature is significantly higher than what is observed (see Rosedale-301 example). Despite the use of averaged regional gradients and the increased uncertainties this brings, the distribution of thermally disturbed bores with a suppressed temperature is completely systematic and clearly delineated (the red line on Figures 1 and 8). All bores to the west of this line have predicted and actual temperatures in accord (variance of up to 10% considered acceptable), whereas to the east the actual temperatures are often 20–40% less than predicted. These unexpectedly low temperatures in the east have previously been noted when they frustrated attempts to model heat flow in the Cainozoic section of this region (Walsh 2009).

In young continental sedimentary basins such as the Gippsland Basin, semi-horizontal permeable layers allow and direct the flow of groundwater, and vertical flow vectors are typically small compared to the horizontal flow vector due to anisotropy of the hydraulic conductivity of the sedimentary rocks (examined in detail for the Gippsland Basin by Schaeffer 2008). Lying above the tight, low-porosity Strzelecki Group and Palaeozoic basement rocks, the Cainozoic sedimentary section broadly contains three aquifer systems: the Latrobe aquifer, capped and sealed by the Lakes Entrance Formation; the Seaspray aquifer/aquitard system; and the Shallow Aquifer System of post-Miocene unconsolidated sands, gravels, and clays (following the definitions of Varma & Michael 2011). Regional groundwater movement is generally from onshore recharge areas – where the aquifers subcrop around the Strzelecki Ranges, along the crest of the Baragwanath Anticline, and along the northern margin of the basin – flowing towards the coastal plains and offshore discharge areas either at producing hydrocarbon wells (Gibson-Poole et al. 2008; Schaeffer 2008) or into subcrops of the aquifer units in the Bass Canyon (Nahm 2002; Varma & Michael 2011).

The Wombat-4 well provides an example where a significant depth of Strzelecki Group has been logged by precision tools (~350 m Strzelecki Group logged; see Figure 6). Temperature gradients through the overlying Latrobe Group average about 60 °C/km, lower than the regional average of about 90 °C/km, possibly due to removal of heat through advection. The temperature gradient curve (green line in Figure 6) also indicates that this temperature anomaly penetrates some 150 m into the upper parts of the tight Strzelecki Group, where gradients of about 30—35 °C/km are reduced to about 25°C/km. From ~1500 m to the base of the temperature log, the gradient is a more typical average of ~30°C/km, suggesting that lower temperature fluids in the overlying Latrobe Group have caused conductive loss in the uppermost Strzelecki Group. The possibility of strong fluid advection in the low-porosity Strzelecki Group sandstones and claystones is small.

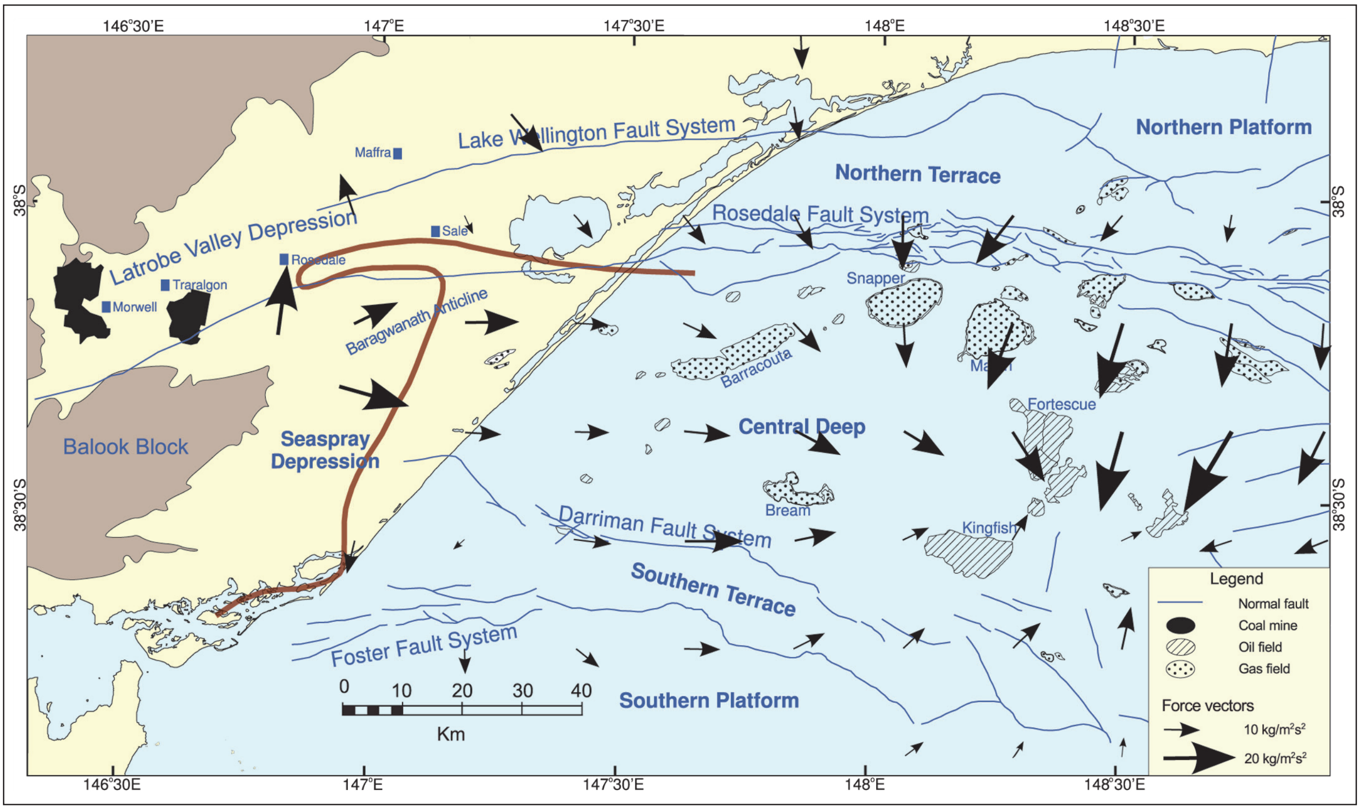

Figure 8. Groundwater flow pattern in the Latrobe aquifer calculated from recent (post-1990s) hydraulic head values of petroleum wells and onshore groundwater level data for 2005 (modified from Varma & Michael 2011).

We agree with the suggestions that temperatures in the Cainozoic section are being suppressed as the result of lateral removal of heat, probably by previously-documented large volumes of groundwater flowing through the Cainozoic stratigraphy, particularly in the eastern near-coastal areas. This region of strong groundwater flow has been mapped by Leonard & King (1992), and more recently by Varma & Michael (2011), and matches the distribution of the thermal anomaly (Figure 8). We also have observed, in a smaller sample, that temperature gradients in the Mesozoic Strzelecki Group satisfy a purely conductive model for the most part (with the exception within Wombat-4 noted above).

Implications for unconventional gas and geothermal resource exploration

The revised and improved understanding of the current day thermal structure allows some new insight into prospectivity for gas and geothermal resources.

With the recent revolution in the exploitation of tight gas and shale gas, basins with potential unconventional resources have become targets of exploration interest. Whilst the current focus in the Gippsland Basin is the large offshore conventional fields, the ease of onshore exploration and the close proximity of Gippsland to major markets and existing infrastructure makes the onshore region worthy of further exploration for unconventional sources. The relatively rapid increase in temperature with depth, as well as a past thermal regime with even higher heat flow and temperature during the Cretaceous rifting means much of the region has been, or remains, within the hydrocarbon generation window. The following summaries speculate on the prospectivity of some commodities in light of the results discussed in the previous sections.

Geothermal

Geothermal prospectivity is enhanced by the presence of thick coal-rich sediments, whose low thermal conductivity results in very rapid temperature increases at relatively shallow depths. Prospectivity is greatest within the Latrobe Valley where the most coal has accumulated. In this region, even if drilling failed to find temperatures high enough for generation of electricity from geothermal fluids, there is some chance of the warm to hot water still being valuable in direct use applications (Leonard & King 1992, Driscoll & Beardsmore 2011). It has also been suggested that feeding warm water in coal-fired steam turbines would reduce the amount of coal needed to be burnt (to warm that water) and that this may prove economically viable (Moghtaderi & Doroodchi 2009). In the Latrobe Valley several large coal-fired generators are situated over the Cainozoic rocks where temperatures reach 60°C in the basal aquifers and perhaps this may prove viable for such input.

Coal Seam Gas

The large region of possible advection (the thermally disturbed zone of suppressed temperature) in the Cainozoic section of the Eastern Depression is interesting for coal seam gas. The groundwater flowing off the highlands and Strzelecki Ranges towards the petroleum production areas could be continually bringing new nutrients into Traralgon Formation coal sequences and removing wastes to enable microbial production of methane (Midgley et al 2010; Strapoc et al 2011). The water flow is mainly in the porous Cainozoic units above the tight Strzelecki Group, which acts as groundwater basement. At the base of the Cainozoic (and thus largely coincident in distribution to the disturbed zone) is the thick and laterally extensive Traralgon coal seams that are a world-class resource of brown coal (Holdgate et al 2000). Here, towards the coast, the boreholes have much lower temperatures than heat flow modelling and gradient analysis predict. In this region, the predicted temperature for the coal seams is close to or overlapping the 50–60°C survival threshold for micro-organisms (Brown 2011), allowing a small possibility of microbial methane generation in the Traralgon Formation.

Tight Gas

For tight gas the Strzelecki Group may be considered the source, reservoir, and seal. The fluvial source rocks are carbon rich with numerous flecks of coal and plant debris clearly visible in core and outcrop samples. Such plant material is likely to have gas-prone kerogen sources (see Mehin & Bock 1998 for a discussion of onshore Gippsland source rocks). Required thicknesses of greater than ~500 m of Strzelecki Group sediments occur throughout the Gippsland Basin, except towards the margins of the basin.

Tight Gas prospectivity is complicated by the fact that VR data from petroleum bores shows that the Strzelecki Group experienced much higher temperatures in the past. Apatite Fission Track Analysis suggests that this happened during the Cretaceous break-up 90-100 Ma (Weber et al. 2004). Hence regions that appear to be in the gas generating window in today's thermal regime could well have in fact already generated in the past.

In the Eastern Depression the top surface of the Strzelecki Group lies at depths up to 1000 m, where temperatures average about 60–70°C. Within the several-kilometres thickness of the Strzelecki Group, temperature increases to at least 150°C so that gas generation is feasible, but there may be some pockets where current temperature exceeds the palaeo-temperature. In the Western Block, the Strzelecki Group is exposed at the surface so that in the present-day temperature regime, only the basal 2–3 km deep section would apparently reach hydrocarbon maturity. This would seem to make this western region less prospective, but this entire region also records similar VR values and hence generated in the Cretaceous. The existence of gas across the entire region – both the eastern depressions and the western block – has been demonstrated by gas shows in wells across the region, such as Megascolides-1 in the west or Wombat-1 and 2 in the east. Much of this area is likely to have already generated gas in the Cretaceous with VR ranging from 0.5-1.7% (see Figure 2; Mehin & Bock 1998).

Shale Gas

Shale gas in North America is largely sourced from deep marine shales with algal kerogen (e.g. Brown 2011) however the Nappamerri Trough in the Cooper Basin in central Australia shows that lacustrine and overbank shales from fluvial basins can also be prospective (Trembath et al. 2012). Dark shales are common in the Strzelecki Group and may prove a source for shale gas.

Summary and Conclusions

New heat flow data collected from boreholes in the onshore Gippsland Basin, including 34 high-precision downhole temperature logs presented here, and nearly 200 thermal conductivity measurements, provide important constraints for future thermal and crustal models. The high accuracy and precision of these data have allowed confident estimates of heat flow for boreholes in the onshore Gippsland Basin, with an average of ~68 mW/m². This value is towards the lower end of previous estimates, which were based on poorly constrained data, but are more consistent with the regional 2D models of Featherstone et al. (1991) and Alexander et al. (1991), and with more recent permit-scale heat flow resource models (e.g. Greenearth Energy Ltd 2009). Additionally, temperature gradient analysis has clearly outlined a thermal anomaly in the Cainozoic section of the Eastern Depression, which is most likely due to heat loss by fluid migration towards the producing oilfields offshore. Importantly, it has been observed that this thermal anomaly is mostly restricted to the Cainozoic section, and only minimally affects temperature gradients in the underlying Strzelecki Group, as exemplified in Wombat-4. Heat flow modellers reliant solely on Cainozoic measurements must take this into account, and seek a broader range of data to support their model.

Bullard Plots have provided a simple means to evaluate the thermal conductivity statistics generated by the broad sampling of drill core throughout the basin, and are a useful tool to accompany interval heat flow analysis. Non-linear trends in Bullard Plots have revealed deviations from the simple 1D heat flow case, and support earlier suggestions of a departure from purely vertical heat flow (Wright 2008).

Numerous measurements show that values for many Cainozoic sediments in the onshore Gippsland Basin have lower thermal conductivity on average than their counterparts as listed in various compilations (e.g. Beardsmore 2001). Moreover, these new measurements are an important resource for the construction of thermal models, and the development of numerical and statistical techniques for thermal conductivity estimation from geophysical well-log data.

Future 2D and 3D modelling using these new data aims to provide even greater insight into the mechanisms and controls of heat flow in the Gippsland Basin.

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Bibliography

ALEXANDER, R., KRALERT, P.G., MARZI, R., KAGI, R.I., EVANS, E.J., 1991. A geochemical method for assessment of the thermal histories of sediments: a two-well case study from the Gippsland Basin, Australia. The APEA journal 31, 325–332.

BARKER, C.E., BONE, Y., LEWAN, M.D., 1998. Fluid inclusion and vitrinite-reflectance geothermometry compared to heat-flow models of maximum paleotemperature next to dikes, western onshore Gippsland Basin, Australia. International Journal of Coal Geology 37, 73–111.

BARTON, C.M., GLOE, C.S., HOLDGATE, G.R., 1993. Latrobe Valley, Victoria, Australia: A world class brown coal deposit. International Journal of Coal Geology 23, 193–213.

BEARDSMORE, G., 2005. High-resolution heat-flow measurements in the Southern Carnarvon Basin, Western Australia. Exploration Geophysics 36, 206–215.

BEARDSMORE, G.R., 2001. Crustal Heat Flow: A Guide to Measurement and Modelling. Cambridge University Press, Cambridge.

BRIGAUD, F., VASSEUR, G. 1989. Mineralogy, porosity and fluid control on thermal conductivity of sedimentary rocks. Geophysical Journal International, 98(3): 525–542.

BROWN, A., 2011. Identification of source carbon for microbial methane in unconventional gas reservoirs. AAPG Bulletin 95, 1321–1338.

CHEN, S., 2008. Thermal conductivity of sands. Heat and Mass Transfer, 44(10): 1241–1246.

CLAUSER, C., HUENGES, E., 1995. Thermal conductivity of rocks and minerals. Rock physics and phase relations: a handbook of physical constants 3, 105–126.

CULL, J.P., 1982. An appraisal of Australian heat-flow data. BMR Journal of Australian Geology & Geophysics 7, 11–21.

CULL, J.P., BEARDSMORE, G.R., 1992. Statistical methods for estimates of heat flow in Australia. Exploration Geophysics, 23, 83–86.

CULL, J.P., CONLEY, D., 1983. Geothermal gradients and heat flow in Australian sedimentary basins. BMR Journal of Australian Geology and Geophysics 8, 329–337.

DRISCOLL, J., 2006. Geothermal prospectivity of onshore Victoria, Australia (Report No. 85), Victorian Initiative for Minerals and Petroleum Report. Department of Primary Industries, Victoria, Australia.

DRISCOLL, J.P., BEARDSMORE, G.R., 2011. Latrobe Valley Shallow Geothermal Project (abs.). Proceedings of the 2011 Australian Geothermal Energy Conference, Record 2011/43:53–62. Melbourne, Australia: Geoscience Australia.

DUDDY, I.R., 2003. Mesozoic: a time of change in tectonic regime, in: Birch, W.D. (Ed.), Geology of Victoria, Geological Society of Australia Special Publication. Geological Society of Australia (Victoria Division), Victoria, Australia, pp. 239–286.

DUDDY, I.R., 1983. The geology, petrology and geochemistry of the Otway formation volcanogenic sediments (Ph.D. thesis). University of Melbourne.

FEATHERSTONE, P., AIGNER, T., BROWN, L., KING, M., LEU, W., 1991. Stratigraphic modelling of the Gippsland Basin. The APEA journal 31, 105–114.

GALLAGHER, K., 1990. Some strategies for estimating present day heat flow from exploration wells, with examples. Exploration Geophysics, 21, 145–159.

GIBSON-POOLE, C., SVENDSEN, L., UNDERSCHULTZ, J., WATSON, M., ENNIS-KING, J., VAN RUTH, P., NELSON, E., DANIEL, R., CINAR, Y., 2008. Site characterisation of a basin-scale CO2 geological storage system: Gippsland Basin, southeast Australia. Environmental Geology 54, 1583–1606.

GOUTORBE, B., LUCAZEAU, F., BONNEVILLE, A., 2006. Using neural networks to predict thermal conductivity from geophysical well logs. Geophysical Journal International 166, 115–125.

GOUTORBE, B., LUCAZEAU, F., BONNEVILLE, A., 2008. Surface heat flow and the mantle contribution on the margins of Australia. Geochemistry Geophysics Geosystems, 9, Q05011.

GREENEARTH ENERGY LIMITED 2009, Statement of Estimated Geothermal Resources: Wombat, GEP13 as at 18 December 2008, ASX Announcement, 5 January 2009. Retrieved from <http://www.greenearthenergy.com.au/reports/>.

GRIFFITHS, C.M., BRERETON, N.R., BEAUSILLON, R., CASTILLO, D., 1992. Thermal conductivity prediction from petrophysical data: a case study. Geological Society, London, Special Publications 65, 299–315.

HALLETT, J.H.J., 2007. Investigation of Heat Flow in the Onshore West Gippsland Basin. (B.Sc. Honours thesis), Monash University.

HARTMANN, A., RATH, V., CLAUSER, C., 2005. Thermal conductivity from core and well log data. International Journal of Rock Mechanics and Mining Sciences 42, 1042–1055.

HOLDGATE, G., GALLAGHER, S.J., 2003. Tertiary: a period of transition to marine basin environments, in: Birch, W.D. (Ed.), Geology of Victoria, Geological Society of Australia Special Publication. Geological Society of Australia (Victoria Division), Victoria, Australia, pp. 289–335.

HOLDGATE, G., WALLACE, M., GALLAGHER, S., TAYLOR, D., 2000. A review of the Traralgon Formation in the Gippsland Basin – a world class brown coal resource. International Journal of Coal Geology.

HOT DRY ROCKS PTY LTD, 2011. Summary of process and data sources used in the development of the EGS Potential maps and tables of Australia. 23 September 2011 unpublished report.

HOWARD, L.E., SASS, J.H., 1964. Terrestrial Heat Flow in Australia. Journal of Geophysical Research, 69, 1617–1626.

IHFC 2010. The Global Heat Flow Database of the International Heat Flow Commission. October 2010 update. Retrieved from http://www.heatflow.und.edu/index2.html.

JESSOP, A.M., 1990. Comparison of industrial and high-resolution thermal data in a sedimentary basin. Pure and Applied Geophysics 133, 251–267.

LEONARD, J.G., KING, R.L., 1992. Low-Enthalpy Geothermal Resources in the Gippsland Basin. Energy, Economics & Environment, Gippsland Basin Symposium 22-23 June 1992, Melbourne, 279–287.

LUO, M., WOOD, J. R., AND CATHLES, L. M., 1994. Prediction of thermal conductivity in reservoir rocks using fabric theory. Journal of Applied Geophysics, 32(4):321–334.

MEHIN, K., BOCK, M.P., 1998. Cretaceous Source Rocks of the Onshore Gippsland Basin, Victoria. Victorian Initiative for Minerals and Petroleum Report 54. East Melbourne, Victoria: Dept. of Natural Resources and Environment, 1998.

MIDGLEY, D.J., HENDRY, P., PINETOWN, K.L., FUENTES, D., GONG, S., MITCHELL, D.L., FAIZ, M., 2010. Characterisation of a microbial community associated with a deep, coal seam methane reservoir in the Gippsland Basin, Australia. International Journal of Coal Geology, 82, 232–239.

MOGHTADERI, B, AND DOROODCHI E., 2009. An Overview of GRANEX Technology for Geothermal Power Generation and Waste Heat Recovery (abs). In Proceedings of the 2009 Australian Geothermal Energy Conference, 11–13 November, Brisbane, Australia.
NAHM, G.Y., 2002. The hydrogeology of the Gippsland Basin, and its role in the genesis and accumulation of petroleum (Ph.D. thesis). University of Melbourne.

NORVICK, M.S., SMITH, M.A., 2001. Mapping the plate tectonic reconstruction of southern and southeastern Australia and implications for petroleum systems. APPEA Journal, Australian Petroleum Production and Exploration Association 41, 15–36.

PECHNIG, R., 2010. Thermal Conductivity of Stratigraphic Units from the Gippsland Basin – Victoria, Geophysica Beratungsgesellschaft mbH, Aachen, Germany. Unpublished Report to the Geological Survey of Victoria.

SASS, J.H., LACHENBRUCH, A.H., MUNROE, R.J., 1971. Thermal conductivity of rocks from measurements on fragments and its application to heat-flow determinations. Journal of Geophysical Research, 76, 3391–3401.

SCHAEFFER, J., 2008. Scaling Point Based Aquifer Data for Developing Regional Groundwater Models: Application to the Gippsland Groundwater System (Ph.D. thesis). University of Melbourne.

SOMERVILLE, M., WYBORN, D., CHOPRA, P., RAHMAN, S., ESTRELLA, D., VAN DER MEULEN, T., 1994. Hot dry rocks feasibility study (No. 94/243). Energy Research and Development Corporation, Australia.

STRĄPOĆ, D., MASTALERZ, M., DAWSON, K., MACALADY, J., CALLAGHAN, A.V., WAWRIK, B., TURICH, C., ASHBY, M., 2011. Biogeochemistry of Microbial Coal-Bed Methane. Annual Review of Earth and Planetary Sciences 39, 617–656.

TAYLOR, D.H., MOORE, D.H., 2010. Victoria's Proterozoic basement intimately controlled the distribution of its southern margin petroleum basins (abs.). APPEA Conference. 16–19 May, Brisbane, Australia.

TEASDALE, J.P., PRYER, L.L., STUART-SMITH, P.G., ROMINE, K.K., ETHERIDGE, M.A., LOUTIT, T.S., KYAN, D.M., 2003. Structural framework and basin evolution of Australia's Southern Margin. APPEA Journal, Australian Petroleum Production & Exploration Association 43, 13–38.

THOMPSON, B.R., 1980. The Gippsland sedimentary basin: a study of the onshore area (Ph.D. thesis). University of Melbourne.

TREMBATH, C., ELLIOTT, L., AND PITKIN, M., 2012. The Nappamerri Trough, Cooper Basin Unconventional Plays: Proving a Hypothesis (abs.). APPEA Conference. 13–16 May, Adelaide, South Australia.

VARMA, S., MICHAEL, K., 2011. Impact of multi-purpose aquifer utilisation on a variable-density groundwater flow system in the Gippsland Basin, Australia. Hydrogeology Journal, 1–16.

WALSH, D., 2009. GEP 12 and 13 temperature logging and heat flow investigation (Confidential report prepared for Greenearth Energy Limited). Hot Dry Rocks Pty Ltd, Melbourne, Australia. Unpublished Report.

WEBER, U. D., K. C. HILL, R. W. BROWN, K. GALLAGHER, B. P. KOHN, A. J. W. GLEADOW, AND D. A. FOSTER., 2004. Sediment Supply to the Gippsland Basin from Thermal History Analysis: Constraints on Emperor-Golden Beach Reservoir Composition. APPEA Journal 44: 397–416.

WOODSIDE, W., MESSMER, J. H., 1961. Thermal conductivity of porous media. I. Unconsolidated sands. Journal of Applied Physics, 32(9): 1688–1699.