Conceptualising Geothermal Exploration Models for Australia and the Development of Thermal Modelling

Anthony R. Budd, Ed J. Gerner, Alison L. Kirkby, and David T. Lescinsky

Geoscience Australia, Canberra ACT

Keywords

Thermal modelling, mappable proxies, exploration, Australia, conceptual models, geothermal exploration

ABSTRACT

Geothermal energy has been harnessed in Australia for several decades for both direct use applications and power generation, but only at very small scale installations. Australia's geothermal resources are amagmatic and unconventional by the accepted definitions in other parts of the world that are centred on active volcanism or plate margin collision. Worldwide, there is a lack of experience in exploring for and developing unconventional resources, and few "deposit" or resource models to aid exploration. The conceptualisation of a range of geological environments amenable to geothermal resource development will underpin the large scale development of geothermal utilisation in Australia. This will include developing exploration models spanning the range of unconventional geothermal resources; from "Enhanced Geothermal Systems (EGS)" or "Hot (Dry) Rock" where permeability stimulation is a pre-requisite, to "Hot Sedimentary Aquifer" where no permeability stimulation is required.

Thermal modelling is being used at Geoscience Australia to develop a set of key minimum criteria for the occurrence of a geothermal resource. From these, mappable proxies will be identified to query a range of geoscience data sets. Thermal modelling work flows are being developed making use of high performance computing, so that models can be run at higher resolution than previously practical, and also so that uncertainty measures can be included. Thermal modelling has been applied in several regions to provide a guide for resource relative potential. Presently, this work is focussed on temperature. The incorporation of permeability estimates will be the subject of future research.

Introduction

In a conceptual framework, geothermal resources require a heat source, and fluid pathways. In amagmatic systems, the heat source is high basal heat flow and crustal heat generation through the decay of naturally occurring radioactive elements. Because of the relatively low heat flux from these sources, thermal insulation is generally required to allow for a temperature increase. Therefore, sedimentary basins, particularly those with low thermal conductivity layers such as coal, are an important part of the "system". As geothermal gradients are low relative to those in actively magmatic areas, temperatures adequate for large scale electricity generation will generally only be reached at depths of 4,000 m or so, and where natural permeability will generally be diminished by lithostatic loading. For this reason there is a growing imperative to better understand variations in both natural permeability and susceptibility to permeability enhancement at depth.

As the geothermal industry develops in Australia, a greater understanding of the ideal geological components of the unconventional system is needed to reduce exploration risk and target the most prospective areas. While a considerable body of borehole temperature data exists, it is very poorly distributed, which limits the reliability of any interpretation of these data (e.g. Holgate and Gerner, 2010). Likewise, heat flow data, which are either available publically or have been shown to be held by companies, is similarly limited in both amount and spatial distribution (Gerner et al., 2011). There are programs being conducted to improve the availability of heat flow determinations however this is an ongoing, time consuming activity, which predominantly relies on access to wells drilled for other purposes.

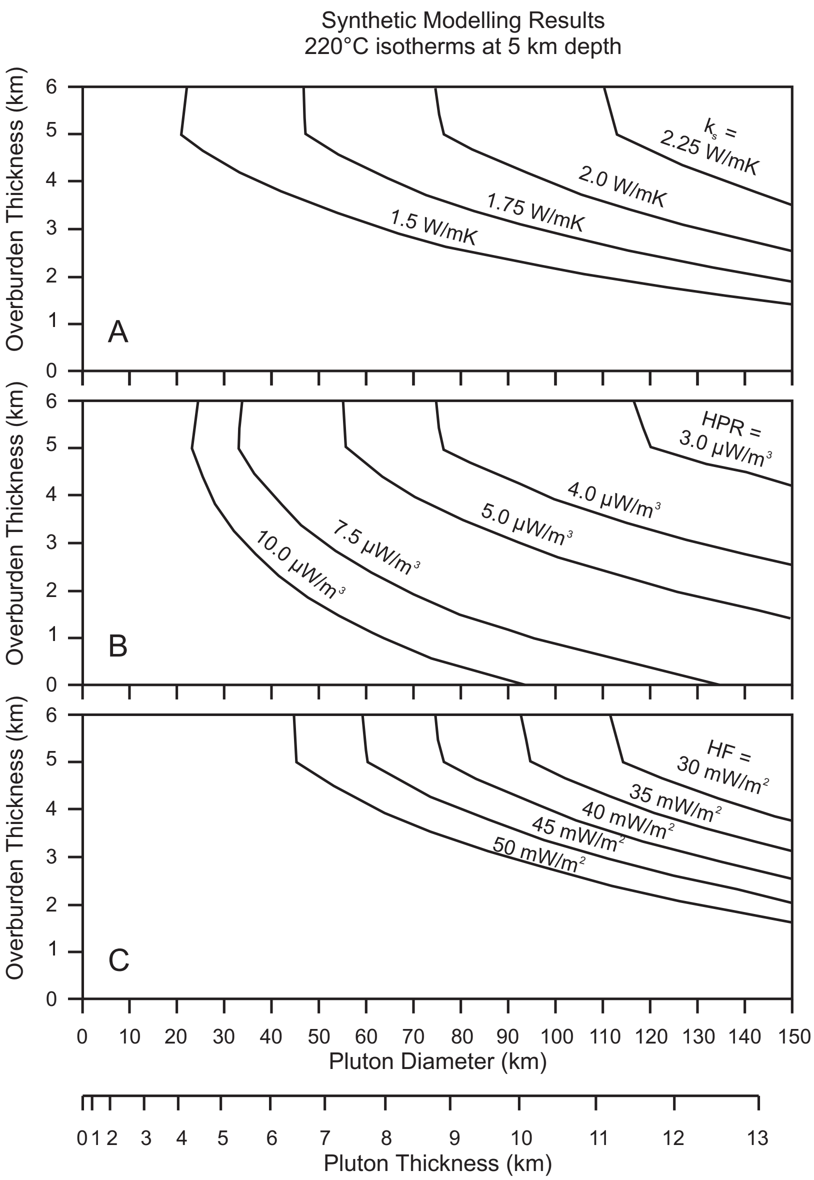
In light of the lack of direct temperature data, there is a need to develop a work flow to help with area identification and prioritisation. Work is being undertaken to define the range of geological bounding conditions required to achieve prospective temperatures. This information when developed is to be used to interrogate other available datasets such as potential field, radiometric and geological data, to identify regions in which the required conditions are likely to exist.

To aid in the definition of the required geological elements a progression of 3D modelling is being undertaken. These models started as highly simplified scenarios to examine the influence of the variables in the system and are developing in complexity as the understanding of the systems improves. In effect, a range of synthetic geological environments are being modelled, hence this work is termed "synthetic thermal modelling".

The estimation and quantification of permeability and permeability susceptibility is the topic of a significant research funding bid by the Geothermal Research Initiative in Australia, and will not be discussed further here.

Identifying Key Parameters

Synthetic models were run to evaluate the importance of the various geometric parameters (pluton dimension, overburden thickness) and thermal parameters (heat production rates, thermal conductivities, basal heat flow). Models were constructed using a wide range of pluton dimensions (diameters of 10-150 km and thicknesses up to 14 km) and overburden thicknesses (1-6 km). Results were evaluated to determine whether a static temperature of 220 °C was achieved at 5 km depth for the given model conditions (Figure 1).



Using the results, it is possible to identify threshold values necessary for achieving the temperature criteria for the different parameters. For the thermal parameters, overburden thermal conductivity and pluton heat production are equally important. In general, where heat production rates (HPR) are less than 4 µW/m^3, insufficient heat is generated, and where thermal conductivities (k) are greater than 2.0 W/mK, insufficient heat is retained. Although these threshold values are dependent on pluton dimension and overburden thickness, the temperature criterion is not met for plutons smaller than 70 km in diameter or for overburden thicknesses of less than 3 km, except for cases with exceptionally high heat production (> 10 µW/m^3) or low thermal conductivity (< 1.5 W/mK). Basal heat flow (HF) has an important, but lesser effect on the modelled temperature, with increasing heat flow (> 40 mW/ m^2) decreasing the threshold values marginally.

Identifying Data Sets for Use as Mappable Proxies

The goal of the synthetic modelling is to develop the key criteria with which to query geological and geophysical data sets. Some such data sets are briefly discussed below.

Size of Granite as Heat Producer

Geometric parameters can be determined using a range of available geophysical data sets. The diameter of buried plutons can be estimated using data sets such as gravity, magnetics and reflection seismics. Although it is complicated and impractical to determine pluton thickness, an average thickness (and thickness range) can be estimated using the pluton diameter and the "best fit" relationship for natural pluton aspect ratios reported by Petford et al. (2000). The relationship describes that plutons generally become more planar as they increase in diameter, following a power-law.

Composition of Granite as Heat Producer

Several approaches can be employed to estimate heat production rates for buried plutons. Separate granite plutons can commonly be grouped into suites on the basis of shared similarities in the field, petrographic and compositional data (White et al. 2001). These

Figure 1. Plots showing the conditions at which the modelled temperature at ~5 km depth is 220°C. Temperatures to the right of each isotherm are >220 °C. A) Models with fixed values of heat production (HPR = 4.0 µW/m^3) and basal heat flow (HF = 40 mW/m^2). B) Models with fixed values of thermal conductivity for overburden (k_s = 2.0 W/mK) and basal heat flow (HF = 40 mW/m^2). C) Models with fixed values of thermal conductivity for overburden (k_s = 2.0 W/mK) and heat production (HPR = 4.0 µW/m^3). Pluton thickness can be determined using the relationship from Petford et al. (2000) described in the text. The kink observed in each isotherm at overburden thickness of five km reflects that at thicknesses greater than five km, the temperature is measured within the sediment overburden, whereas for lower thicknesses the temperature is measured within granite.

similarities mean that suites may be able to be mapped beneath cover from their geophysical signature. Laboratory measurements of heat production by samples of plutons exposed at the surface may be used to assign likely values of heat production to buried plutons on a regional basis. This approach can be corroborated by radiometric surveys of near surface concentrations of radioactive isotopes (Th, U, and K).

Thickness of Basin as Insulator

Basin thicknesses can be estimated using the OzSeeBase (De Vries et al., 2006) GIS product which including layers of sediment thickness. This data set is useful on a national scale. For more detailed mapping, existing basin-scale compilations are available for most basins in Australia, built using drill data, reflection seismic, and gravity and magnetic inversion.

Thermal Conductivity of Basin as Insulator

Estimating the thermal conductivity of basin fill/overburden is possibly the most problematic. Although theory and modelling demonstrate that the vertical sequence of lithologies is not important, existing estimates of the cumulative thicknesses of different lithologies are sparse. It is therefore advantageous to employ a proxy for thermal conductivity. Low values of thermal conductivities (< 2.0 W/mK) can be achieved by uniformly fine-grained sediments (mudstone), but this situation is uncommon. An alternative and more common scenario is the presence of coal beds (average of 0.3 W/mK) within higher conductivity sediments. Calculations show that thermal conductivities of 2.0 W/mK can be achieved for overburden with a thermal conductivity of 2.5 W/mK and as little as 3 % coal. This suggests that coal maps and estimates of coal thickness can be used as a proxy for low thermal conductivity.

3D Thermal Modelling on a Regional Scale

Once high potential regions have been identified using mappable proxies, regional assessments can be performed to gain a more detailed, ideally quantitative, understanding of temperature at depth and its uncertainty.

In the past, regional assessments of geothermal potential done at Geoscience Australia have been based on either direct interpolations between heat flow determinations and direct temperature measurements or a qualitative GIS-based approach (e.g., Ayling and Lewis, 2010). More recently, we have applied a 3D forward modelling approach (Meixner et al., 2011) whereby a geological model is built that incorporates the main heat-producing and insulating units. The model is then assigned thermal properties and used in conjunction with thermal modelling software to predict the temperature distribution at depth. The advantage of this approach is that the results can be compared with direct temperature and heat flow measurements, allowing the input parameters to be updated to give a better match to the data. However this approach is much more computationally intensive than a GIS-based approach, and as a result, uncertainty has as yet been assessed only qualitatively.

Two methods are being examined to assess quantitative uncertainty using the Cooper Basin region, South Australia, as a test area: a stochastic approach, and Monte Carlo modelling. Both approaches utilise the National Computational Infrastructure Facility 10,000 core supercomputer at the Australian National University. With stochastic modelling, a suite of models are run based on a mean and standard deviation defined for each input parameter (Gibson et al., 2010). A mean and standard deviation temperature value at each point in the model volume is returned. With a Monte Carlo approach, a suite of models are run, with input parameters randomly selected from a distribution defined for each parameter. The output models can then be filtered, retaining only models that fit satisfactorily with measured temperature and heat flow data. From the remaining models, the mean temperature and its standard deviation is then calculated at every cell in the model. We use an implementation of PyShemat (Wellman et al., 2011) combined with internally developed code.

Discussion

Predicting temperature in areas of good data is well understood. However, Australia has vast areas with no temperature (or heat flow) data, with poorly constrained geology at depth. The thermal modelling methods being developed, in combination with a conceptual approach to the development of unconventional geothermal resource models, will allow estimation of temperature at depth with uncertainty quantification in areas of sparse data. The focus of the synthetic thermal modelling has been on understanding what the key parameters are for heat generation and accumulation, and what the lower limits on these are so that criteria can be established to query other geological data sets to map areas of potential.

Conclusion

In the absence of empirical evidence, a conceptual approach is being followed to build an understanding of geothermal exploration models for application in the amagmatic geological terranes of Australia. This work is presently focussing on temperature as being the more amenable of two requirements for a geothermal resource: temperature, and flow pathways. Early results of this work indicate that thermal insulation is a critical parameter, with crustal heat generation and basal heat flow being less of an influence. This understanding will be translated to map form through the development of mappable proxies.

Acknowledgements

This paper is published with the permission of the Chief Executive Officer, Geoscience Australia.

References

Ayling, B., and B. Lewis, 2010. "Geothermal Systems." In: *Huston, D.L. (ed), An assessment of the uranium and geothermal potential of north Queensland.* Geoscience Australia Record, 2010/14, p68-91.

De Vries, S.T., N. Fry and L. Pryer, 2006. "OZ SEEBASE™ Study 2005." Public domain report to Shell Development Australia by FrOG Tech Pty Ltd. GIS and report, available from www.frogtech.com.au.

Gerner, E.J., A.J. Meixner, A.L. Kirkby, R.D. Weber, D.C. Champion, A.R. Budd and T. Jones, 2011. "Heat flow determinations and geothermal potential assessment of the Australian continent: Support for an emerging geothermal industry." *GRC Transactions, Volume 35*, 791-794.

Gibson, H., R. Seikel and T. Meixner, 2010. "Characterising uncertainty when solving for 3D temperature: New tools for the Australian geothermal energy exploration sector." Australian Society of Exploration Geophysicists Extended Abstracts 2010(1), 3pp, doi:10.1071/ASEG2010ab290.

Holgate, F.L., and E.J. Gerner, 2010. "OzTemp Well temperature data." Geoscience Australia. Available from https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=70604.

Meixner, A.J., A.L., Kirkby, D.C., Champion, R.D., Weber, D., Connolly, and E.J., Gerner, 2011. "Geothermal Systems." In: *Huston, D.L., and van der Wielen, S.E. (eds), An assessment of the uranium and geothermal prospectivity of east-central South Australia.* Geoscience Australia Record, 2011/34, p166-210.

Petford, N., A.R., Cruden, K.J.W., McCaffrey, and J.-L., Vigneresse, 2000. "Granite magma formation, transport and emplacement in the Earth's crust." *Nature*, 408, p669-673.

Wellmann, J.F., A. Croucher and K. Regenauer-Lieb, 2011. "Python scripting libraries for subsurface fluid and heat flow simulations with TOUGH2 and SHEMAT." *Computers and Geosciences*, doi:10.1016/j.cageo.2011.10.011.

White, A.J.R., C.M. Allen, S.D. Beams, P.F. Carr, D.C. Champion, B.W. Chappell, D. Wyborn and L.A.I Wyborn, 2001. "Granite suites and supersuites of eastern Australia". *Australian Journal of Earth Sciences* 48/4, p515-530.